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PSI-1012/
TR-757

SURVEY OF LASER-PRODUCED PRESSURE AND IMPULSE DATA

Final Report

Contract Number: N00014-86-C-2241

for

The Naval Research Laboratory
4555 Overlook Avenue, S.W.
Washington, DC 20375-5000

by

J.A. McKay and P.M. Laufer

September 1987

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The objective of the present work is the collection of all laser-generation pressure and impulse data of good quality, and the display of those data in a single format. It should now be possible not only to discover what data regimes have been investigated and which neglected, but to compare experimental results for consistency and the detection of overall patterns.

The data are organized first by pressure and impulse, then by the ambient conditions, i.e., in air, in reduced-pressure air, and in vacuum. Within each category the reports are organized by wavelength, beginning with the middle infrared and proceeding to the ultraviolet. Within each wavelength category the data are presented in chronological order of publication.

The graphic display of each set is selected to emphasize the most important single variable.

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PREFACE

This report is a compilation of all laser-produced impulse and pressure generation data pertinent to laser effects and damage work. The work was undertaken at the inspiration of Dr. D.J. Nagel of the Naval Research Laboratory, who recognized the liabilities of having laser effects data scattered through innumerable conference reports and contractor papers. This work attempts to present, in a unified format, all data currently available, as a guide not only to the pressure and impulse levels which can be expected under any conditions but as an indication of the laser regimes which either have been thoroughly worked and therefore warrant no further investigation, or which have been neglected.

The work was performed from August 1986 through August 1987. This is one part of the survey performed under this contract, the others dealing with impulse and pressure measurement devices and techniques. These are complete and are currently in the final publication process.

SURVEY OF LASER-PRODUCED PRESSURE AND IMPULSE DATA

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SURVEY OF LASER-PRODUCED PRESSURE AND IMPULSE DATA

INTRODUCTION

A great volume of laser-generated pressure and impulse data exists, but is scattered through journals, Government contract reports, and conference presentations, many of the latter classified even when the data themselves are not. Not only is it very difficult and time-consuming to collect these data, but comparison of data between experiments is complicated by differing means of data presentation. The objective of the present work is the collection of all laser-generated pressure and impulse data of good quality and the display of those data in a single format. It should now be possible not only to discover what data regimes have been investigated and which neglected, but to compare experimental results for consistency and the detection of overall patterns.

This allows, for example, an evaluation of data across many orders of magnitude in laser intensity. Single experiments are generally confined to relatively restricted ranges of intensity, but laser work over the past two decades will be seen to have covered at least 8 orders of magnitude. A comparison of only a few experiments across such a range is unreliable, but an examination of numerous experiments filling the range can expose aberrant sets of data and emphasize the more reliable general trends.

Six categories of data will be found in the following pages, in a matrix of pressure and impulse data, and measurements in air, in vacuum, and in reduced-density air. The numbers of works in each category are as follows:

	Air	Vacuum	Reduced-density air
Pressure	11	4	4
Impulse	17	28	1

The larger number of impulse reports in the principal categories reflects, presumably, the relative ease of impulse measurements versus pressure (target stress) measurements. In many vacuum works, impulse gauge measurements are reported as pressure data through the simple artifice of dividing by the pulse duration. We have insisted on presenting the actual parameter measured, in this case the impulse rather than the pressure, in order to avoid the implicit assumption that the pressure pulse coincides with the laser pulse.

Within each category the reports are organized by wavelength, beginning with the middle infrared and proceeding to the ultraviolet. Within each wavelength category the data are presented in chronological order of publication.

The graphic display of each set is selected to emphasize the most important single variable. The choice of that single variable, necessary to bring about the unified display of data, is not necessarily easy. For pressure measurements in air, for example, the choice is straightforward: the single critical variable is the laser irradiance, the only laser parameter appearing in the Raizer expression for the peak detonation-wave pressure. For impulse measurements in

air the choice is much more difficult, since all the laser parameters enter into the impulse coupling. In this case the choice has been made, perhaps arbitrarily, to display the coupling results against total laser energy. This avoids a comparison of small-spot impulse data to big-laser data, a comparison that could be very misleading due to the strong dimensionality effects of impulse generation in air. Unfortunately the difficulty remains that large long-pulse lasers will appear to be the same as large short-pulse lasers, leading to the same dimensionality conflict. There is no way, with two-dimensional plots, to resolve this problem.

The distribution of laser wavelengths employed in these measurements is perhaps an indication of where further work is needed. Naturally, the relatively common CO2 and Nd lasers lead:

	Pressure			Impulse		
	Air	Vac	Reduced air	Air	Vac	Reduced air
CO2	7	2	4	5	6	1
HF/DF	1	0	0	1	1	0
I2	0	0	0	1	0	0
Nd	2	0	0	8	9	0
Ruby	0	0	0	1	1	0
XeF	0	2	0	1	8	0
KrF	0	0	0	1	3	0

The paucity of work at reduced ambient pressure is clear. This prevails despite warnings that the interaction of laser pulses with targets at high altitude is a regime of substantial uncertainty. No experimental proof exists that the model-predicted variations of air-plasma coupling with air density are valid; and there are no reliable models for predicting the density at which the transition from an air-mediated interaction to a direct target-material interaction will occur. The extensive survey of coupling work conducted for this report yielded practically nothing applicable to these issues.

While every effort was made to have this survey be complete, the limitations of time and budget, and the difficulty of tracking down work consigned to unpublished reports, will have left some omissions. Work from every relevant field was included, specifically including coupling experiments performed in support of laser-fusion research and experiments performed with material surface modification in mind, as well as the obvious category, work performed for the Department of Defense for weapons applications.

MODELS FOR PRELIMINARY DATA-THEORY COMPARISONS

Three models have been used for a very modest comparison of experimental data to theory. Plainly more sophisticated modeling is required for rigorous interpretation of the data, but the elementary models used here will provide a starting point for that interpretation, and are amenable to quick calculation over the wide range of variable parameters represented by this data compilation.

1. Peak pressure, air: Pirri/Raizer model.

The Raizer expression for the air pressure behind a laser-driven detonation wave is well known [1]. Pirri [2] deduced the factor for the LSD pressure at a fixed surface. Air as an ideal gas with gamma = 1.18 is assumed here. The surface pressure (equal to the stress that would be measured immediately within the target surface) is given by

$$P_s = 684\ (\text{density})^{1/3}\ \phi^{2/3} \quad , \tag{1}$$

where P_s is in dynes/cm^2 (10^6 d/cm^2 $\equiv$ 1 bar), the density is referred to the sea-level value of 1.22×10^{-3} g/cm^3, and ϕ is the irradiance in W/cm^2.

2. Impulse in air: Simons model.

Impulse generation by a laser pulse in air is essentially an instantaneous explosion followed by a blast-wave decay, the latter contributing, in most cases, most of the impulse. It is possible to model impulse generation quite satisfactorily by considering the blast-wave decay as the impulse generator while neglecting the details of pressure-time during the laser pulse itself. The model used here is due to G.A. Simons of Physical Sciences Inc [3].

Others have patched blast-wave solutions to obtain expressions for impulse delivery by laser pulses [4, 5]. These patching sequences do not, however, conserve the energy of the blast wave. The essence of the present model is the careful selection of patch times such that energy is conserved, even at the expense of the precision of the details of the description of the pressure-time history. The result is a more accurate determination of the total impulse delivery, while the details of the pressure-time obtained from the model are imperfectly represented.

The Simons model leads to a definition of eight distinct regimes, each corresponding to a certain permutation of inequalities involving the laser pulse duration, the laser spot diameter, and the laser target dimensions (the latter being quite important due to radial expansion across the target surface, a factor frequently unappreciated in experimental work). A modest computer program has been written to determine the appropriate regime and calculate the coupling coefficient for plotting on the various data charts.

3. Peak pressure and total impulse in vacuum: Pirri model.

The Pirri model for pressure and impulse delivery by a laser pulse in vacuum [6] is a steady-state ablation model, assuming a laser beam focussed to a spot small enough that radial vapor flow permits plume clearing and allows the laser radiation to continue to reach the material surface, albeit attenuated. This is similar to the well-known Basov approach [7]. The essential result is an expression for the pressure generated at the target surface. The impulse is supposed to be simply the product of this pressure, the pulse duration, and the spot area, neglecting possible phenomena such as vapor-pressure decay and radial expansion of ablation due to vapor expansion.

Pirri's expression for the pressure at the target reduces to

$$P_s = 0.0425 \left[M^{7/2} c^2 \phi^7 / r_s l^2 \right]^{1/9} , \quad (2)$$

where

P_s = peak pressure in d/cm²
M = atomic weight of the target material, amu
c = speed of light,
l = laser wavelength, in units consistent with c,
r_s = spot radius, cm, and
ϕ = laser irradiance, W/cm².

The impulse coupling coefficient is given by

$$I/E = 0.0425 \left[M^{7/2} c^2 / \phi^2 r_s l^2 \right]^{1/9} , \quad (3)$$

in dyne-seconds/joule.

REFERENCES:

[1] Yu. P. Raizer, "Propagation of discharges and maintenance of a dense plasma by electromagnetic fields", Sov. Phys. Uspekhi 15, 688-707 (1973); ibid., "Heating of a gas by a powerful light pulse", Sov. Phys. JETP 21, 1009-1017 (1965).

[2] Anthony N. Pirri, "Theory for momentum transfer to a surface with a high-power laser", Phys. Fluids 16, 1435-1440 (1973).

[3] Girard A. Simons, "Momentum transfer to a surface when irradiated by a high-power laser", AIAA Journal 22, 1275-1280 (1984).

[4] A.N. Pirri, "Theory for momentum transfer to a surface with a high-power laser", Physics of Fluids 16, 1435-1440 (1973).

[5] J.P. Reilly, A. Ballantyne, and J.A. Woodroffe, "Modeling of momentum transfer to a surface by laser supported absorption waves", AIAA Journal 17, 1098-1105 (1979).

[6] Anthony N. Pirri, "Theory for laser simulation of hypervelocity impact", Phys. Fluids 20, 221-228 (1977).

[7] N.G. Basov, V.A. Gribkov, O.N. Krokhin, and G.V. Sklizkov, "High temperature effects of intense laser emission focused on a solid target", Sov. Phys. JETP 27, 575-582 (1968).

PRESSURE DATA IN AIR (NOMINAL 1 ATM DENSITY):

#	1st author	yr	wavel	matls
B35	Hettche	1973	10.6	aluminum, commercially pure
B13	Beverly	1976	10.6	aluminum, PMMA, cellulose acetate
B17	Boiko	1977	10.6	Aluminum, lead, titanium
B16	Ready	1978	10.6	Steel, aluminum, potassium chloride
A05-1	Holmes	1981	10.6	Pyroceram, slip-cast fused silica (SCFS), Cordopreg, fiberglass
A06	Tucker	--	10.6	aluminum
B1	Dufresne	1981	10.6	aluminum
A05-2	Holmes	1981	3.8	2024-T3 aluminum, 6Al-4V titanium, fiberglass
B33	Hettche	1976	1.06	1100 Al, Ti-6Al-4V
ETI	King	1983	1.06	aluminum, carbon (Grafoil, rolled graphite)
T3	Holmes	1986	1.06	aluminum, carbon (Grafoil, rolled graphite)

PRESSURE (STRESS) DATA IN AIR

The following figures show the data obtained for peak-stress measurements in air at ordinary (laboratory-altitude) density. The data are shown versus laser irradiance, the predominant independent variable for stress/pressure measurements in general. The range of irradiance is from 1×10^6 W/cm^2 to 1×10^{11} W/cm^2, the lower limit set by the threshold for plasma ignition at the longest wavelength of concern (10.6 μm), the upper by the maximum intensity that can be propagated in full-density air without laboratory-air breakdown. The peak pressure is shown in bars (1 bar $\equiv 10^5$ Pa $= 10^6$ d/cm^2).

A major advantage of stress measurements over impulse measurements is the obtaining of a one-dimensional line of data -- the stress versus time -- instead of single point measurement. We have not attempted to show stress-versus-time data here, due to practical limitations.

Shown on each plot is a theoretical line for the peak pressure of a laser-supported detonation wave (LSD). The Raizer expression for the air pressure behind an LSD wave is well known [1]. Pirri [2] deduced the factor for the LSD pressure at a fixed surface. Air as an ideal gas with gamma = 1.18 is assumed here. The surface pressure (equal to the stress that would be measured immediately within the target surface) is given by

$$P_s = 684\ (\text{density})^{1/3}\ \phi^{2/3} \quad , \qquad (1)$$

where P_s is in dynes/cm^2 (10^6 d/cm$^2 \equiv 1$ bar), the density is referred to the sea-level value of 1.22×10^{-3} g/cm^3, and ϕ is the irradiance in W/cm^2.

The principal feature of Eq. (1) is the $\phi^{2/3}$ dependence, and the absence of any dependence on any other laser parameters, such as the pulse duration, the wavelength, and the spot dimensions. The peak pressure is also quite independent of the target material, since only air is involved in the interaction. Spectroscopy experiments on laser-driven air plasmas ignited at target surfaces have confirmed that there is little material vapor in the plasma, though air seeding by the target material is believed to be essential for plasma ignition [3].

The independence of the peak pressure of all the interaction parameters but the laser irradiance permits a legitimate comparison of all peak-pressure data on a single plot. The result shows very good agreement between experimental data and the Pirri/Raizer expression. Exceptions occur where the irradiance is close to ignition threshold, reducing the pressure, and where the air plasma is superseded by fast target vaporization, which can generate pressures well above the Pirri/Raizer value.

Other exceptions are a regime of a laser-supported combustion wave (LSC) at low intensities, and a regime of UV-photon plasma propagation, at very high intensities. The canonical LSD propagates by the shock wave itself heating the air to a level such that the air becomes opaque, and highly absorbing, to the laser irradiation. At low levels the shock can be too weak for this conversion to absorption to occur. The plasma then expands by thermal conduction from the hot gas, heating cold air to laser opacity, the LSC. This mode yields lower

expansion velocities and higher peak pressures, and may be evident in the data, though the departure from the LSD line is small.

At high levels a peculiar thermal-conduction mode of propagation can displace the shock-wave expansion mode. Called the "hyperdetonation" wave by Raizer, this proceeds by radiation from the very hot plasma in the vacuum ultraviolet heating the air to laser opacity. The hyperdetonation mode can prevail if its velocity exceeds the detonation wave velocity, i.e. the thermal-conduction wave precedes the shock. This mode has been quite clearly observed at the highest laser intensities explored in air. The higher expansion speed leads to a lower peak pressure, though again the departure from the LSD line is small. All these propagation modes have been treated by Raizer [4].

Peak pressures generated by lasers in full-density air appear to be quite well understood and explored.

REFERENCES:

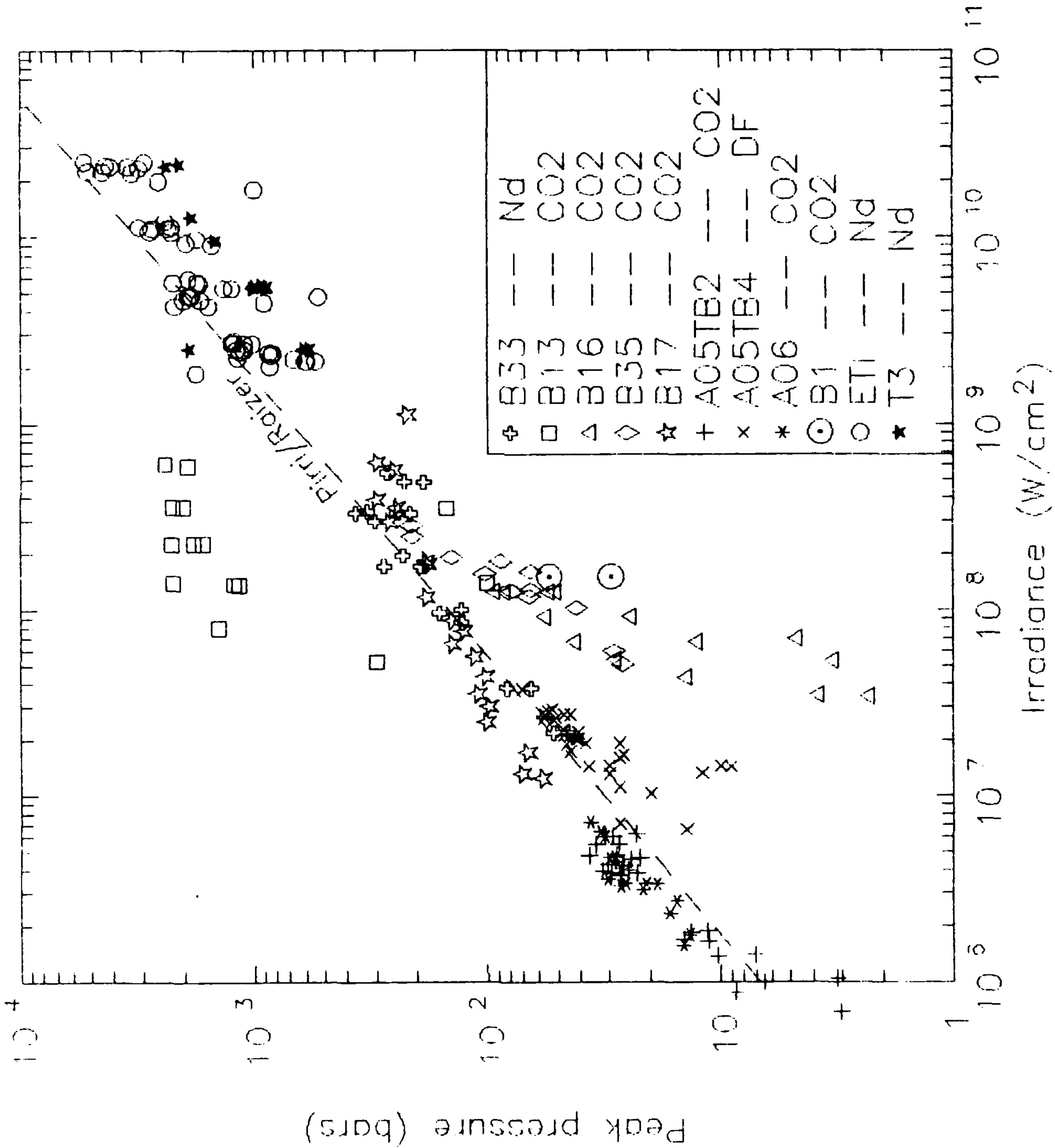
[1] Yu. P. Raizer, "Propagation of discharges and maintenance of a dense plasma by electromagnetic fields", Sov. Phys. Uspekhi 15, 688-707 (1973); ibid., "Heating of a gas by a powerful light pulse", Sov. Phys. JETP 21, 1009-1017 (1965).

[2] Anthony N. Pirri, "Theory for momentum transfer to a surface with a high-power laser", Phys. Fluids 16, 1435-1440 (1973).

[3] G. Weyl, A. Pirri, and R. Root, "Laser ignition of plasma off aluminum surfaces", AIAA J. 19, 460-469 (1981); E.V. Dan'shchkov, V.A. Dymshakov, F.V. Lebedev, and A.V. Ryazanov, "Breakdown of atomic gases by CO_2 laser radiation near metal surfaces", Sov. J. Quantum Electron. 12, 62-66 (1982).

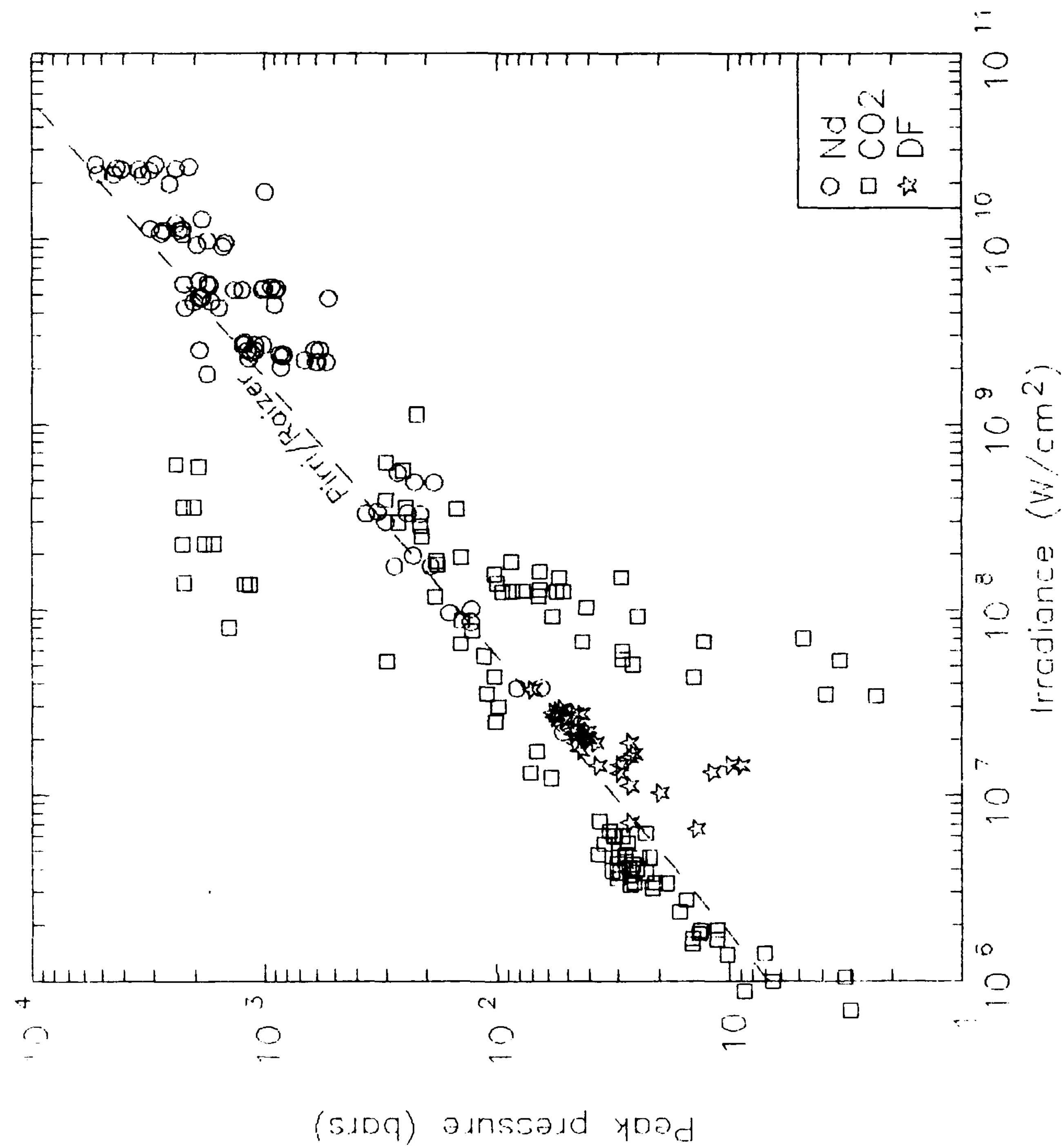
[4] Yu. P. Raizer, "Propagation of discharges and maintenance of a dense plasma by electromagnetic fields", Sov. Phys. Uspekhi 15, 688-707 (1973).

Display of all peak-pressure data in normal-density air. The Pirri/Raizer line is reasonably successful at describing the peak pressure across eight orders of magnitude in laser irradiance. Substantial divergences from the Pirri/Raizer line occur in two cases: at low irradiance, where ignition threshold effects reduce the peak pressure; and for short pulses on ablating targets, where the sharp spike generated by target ablation can exceed the air-plasma pressure level. The ignition threshold is, of course, wavelength-dependent, increasing with decreasing wavelength. Smaller discrepancies between the Pirri/Raizer line and the data appear where a combustion wave (LSC) is formed, at low laser irradiance, and where a hyperdetonation wave is formed, at very high laser irradiance.



Peak pressure (bars)
Irradiance (W/cm^2)
1
10
10^2
10^3
10^4
10^5
10^7
10^8
10^9
10^{10}
10^{11}
Pirri/Raizer
B33 — Nd
B13 — CO2
B16 — CO2
B35 — CO2
B17 — CO2
A05TB2 — CO2
A05TB4 — DF
A06 — CO2
B1 — CO2
ETI — Nd
T3 — Nd

Again displaying all the data compiled, but now with symbols to distinguish between the three laser wavelengths employed.



Nd
CO2
DF
Pirri/Raizer
Irradiance (W/cm²)
Peak pressure (bars)
10⁵
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹
1
10
10²
10³
10⁴

Reference # : B35

Authors : L.R. Hettche, J.T. Schriempf, and R.L. Stegman

Citation: "Impulse reaction resulting from the in-air irradiation of aluminum by a pulsed CO_2 laser", J. Appl. Phys. 44, 4079-4085 (1973)

Institution: Naval Research Laboratory, Washington DC

Experimental Conditions:

Laser: electron-beam-pumped CO_2
- Wavelength: 10.6 μm
- Pulse energy: 100-700 J
- Pulse duration: 15-50 μs

Intensity range: 1×10^7 - 1×10^8 W/cm^2

Atmosphere: 1 atm air

Spot dimensions: 47% of energy within 0.1 cm^2, 43% in four symmetrical lobes (about 0.4 cm^2)

Target materials: aluminum, commercially pure

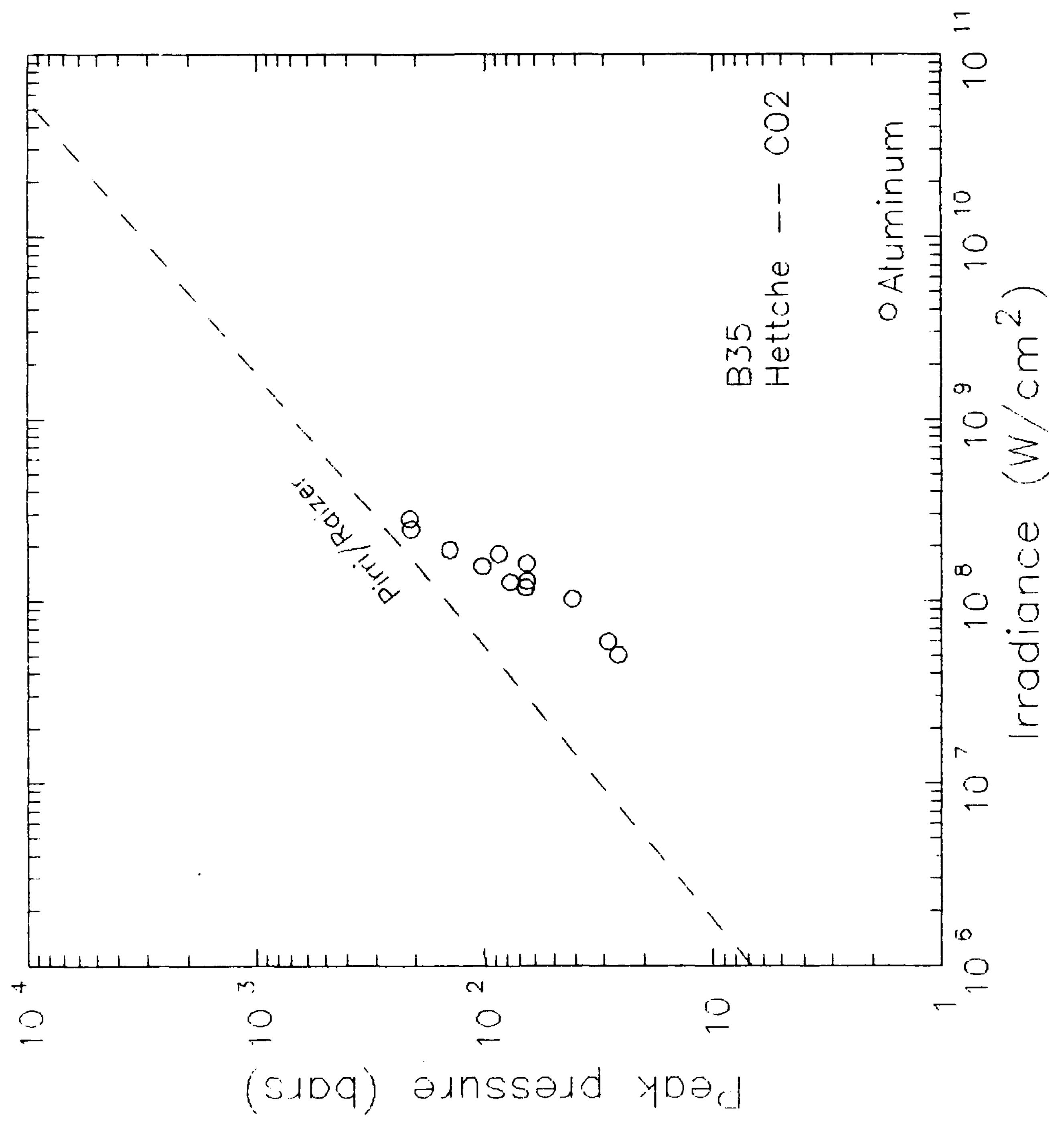
Target dimensions: 3.5 cm diameter, 0.05 cm thick

Measured quantities: pressure

Measurement technique: laser displacement interferometer, viewing silvered face of quartz rod to which target disks were attached

Figure caption: "The peak pressure generated during the initial stages of plasma-surface interaction is seen to vary as the second power of the power density. The ratio of the pressure to power density is proportional to the instantaneous impulse coupling coefficient."

Comments: These data lie significantly below the Raizer-Pirri line, due possibly to the very poor spatial profile, causing not only great difficulty in characterizing the effective irradiance but possibly strong two-dimensional effects in the nonuniform plasma.



B35
Hettche — — CO2
○ Aluminum
Pirri/Raizer
Peak pressure (bars)
Irradiance (W/cm^2)
1
10
10^2
10^3
10^4
10^6
10^7
10^8
10^9
10^{10}
10^{11}

Reference # : B13

Authors : R. E. Beverly, III, and C. T. Walters

Citation: "Measurement of CO_2-laser-induced shocks above and below LSD-wave thresholds", J. Appl. Phys. 47, 3485-3495 (1976)

Institution: Battelle Columbus Laboratories, Columbus OH

Experimental Conditions:

Laser: TEA CO_2

Wavelength: 10.6 μm

Pulse energy: 80 J

Pulse duration: 80 ns fwhm plus "several microseconds" N_2 tail

Intensity range: 3.2×10^7 - 5.8×10^8 W/cm^2 (varied with attenuators)

Atmosphere: 1 atm air to vacuum (1×10^{-7} Torr)

Spot dimensions: 0.61 cm diameter (0.29 cm^2 area) (fixed)

Target materials: Aluminum, PMMA, cellulose acetate

Target dimensions: 5 cm diameter (carbon gauge specimens); 0.7, 1.14 cm diameter (quartz gauge specimens)

Measured quantities: pressure

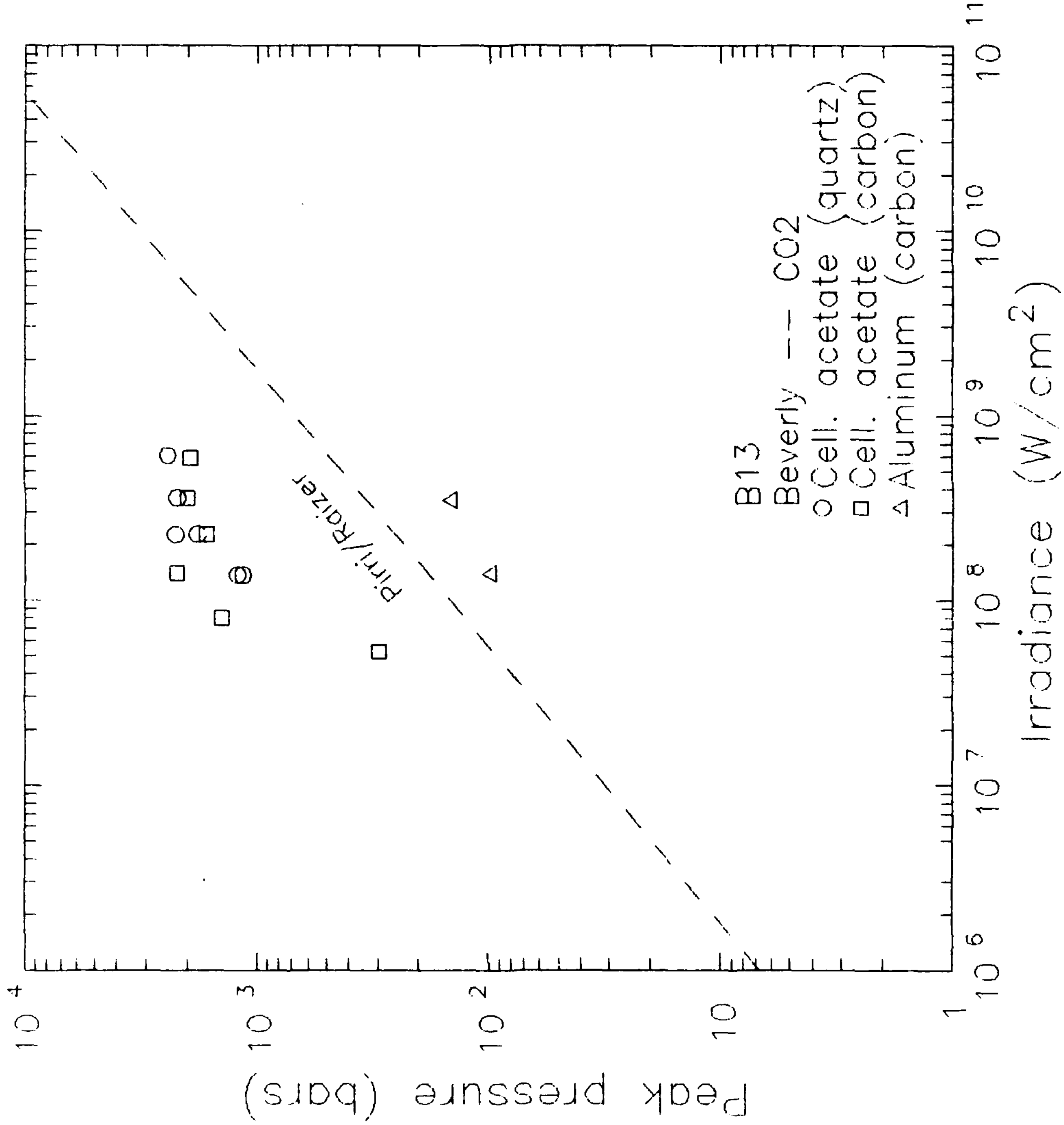
Measurement technique(s):

(1) quartz piezoelectric (Sandia type, shorted), 0.318 cm active diameter, 0.127 cm length (220 ns writing time); silicone grease bond to target

(2) carbon piezoresistive (Dynasen), 0.13x0.15x0.0036 cm; epoxied onto front face of 3.2 cm thick backup disk, then epoxied or silicone-bonded to target disk, yielding an embedded gauge

Figure caption: "Peak shock pressure in cellulose acetate as a function of peak power density for an ambient pressure of 760 Torr. Experimental data are shown for both quartz and carbon gauge measurements." Peak pressure data for aluminum are also shown here.

Comments: "The magnitude of the peak pressure [on cellulose acetate] in all cases is very much greater than that which can be generated by LSD-wave pressures. This implies that the peak pressure response in the case of the plastics is dominated entirely by vapor blow-off. . . . The peak pressure levels [on aluminum] are lower than predicted by theory, as would be expected for local initiation and surface imperfections and defect sites and for a short pulse width."



B13
Beverly -- CO2
Cell. acetate (quartz)
Cell. acetate (carbon)
Aluminum (carbon)
Pirri/Raizer
Irradiance (W/cm^2)
Peak pressure (bars)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
1
10
10^2
10^3
10^4

Reference # : B17

Authors : V.A. Boiko, V.A. Danilychev, B.N. Duvanov, V.D. Zvorykin, I.V. Kholin, and A. Yu. Chugunov

Citation: "Measurement of gasdynamic pressure on a target subjected to CO_2 laser radiation", Sov. J. Quantum Electron. 7, 465-468 (1977)

Institution: P.N. Lebedev Physics Institute, Moscow

Experimental Conditions:

Laser: e-beam CO_2

Wavelength: 10.6 μm

Pulse energy: 100 J

Pulse duration: 120 ns fwhm, 450 ns total.

Intensity range: 1×10^7 - 1×10^9 W/cm^2

Atmosphere: 1 atm to vacuum (0.07 Torr)

Spot dimensions: 0.5 - 3 cm^2

Target materials: Aluminum, lead, titanium

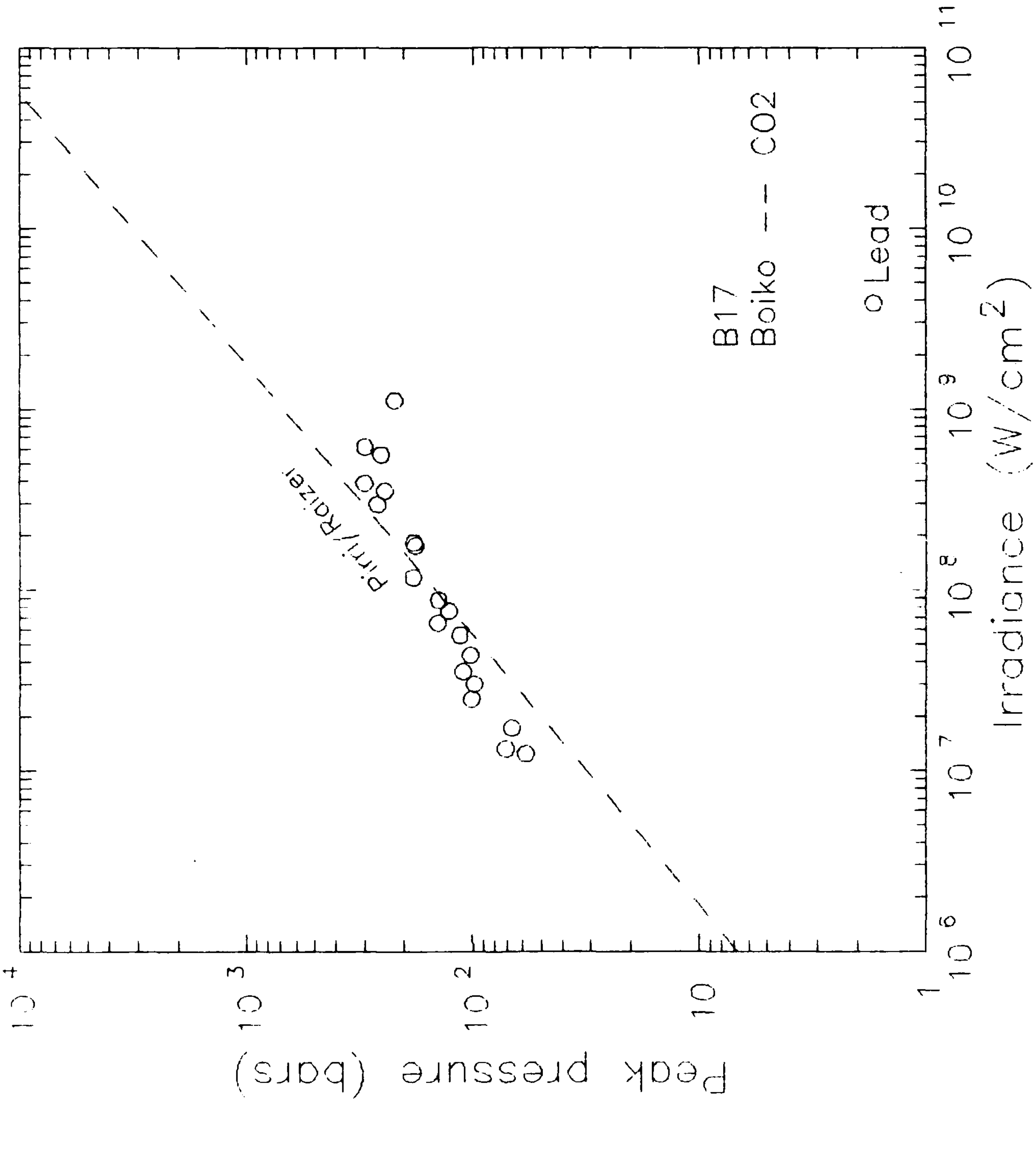
Target dimensions: 1 cm diameter foils, thickness 0.7 mm (Pb), 0.15 mm (Al), 0.05 mm (titanium).

Measured quantities: pressure

Measurement technique: quartz piezoelectric (Sandia type), 0.4 cm active diameter, 0.1 cm length (175 ns writing time); in "acoustic contact" with target specimens

Figure caption: "Experimental . . . dependences of the amplitude of the pressure on a target in air on the maximum laser power density (energy density) obtained for [spot area] 0.5, 1.1, 3.0, and 1.6 cm^2, Pb, Al, Ti targets." In the original, symbols distinguish among spot sizes and target materials. The differences are insignificant.

Comments: In contrast to the measurements by Ready (B16), these data show excellent agreement with the Raizer-Pirri theory. The absence of a material dependence supports the conclusion that the pressure is developed by an LSD, rather than by target vaporization.



B17
Boiko -- CO2
o Lead
Pirri/Raizer
Peak pressure (bars)
Irradiance (W/cm²)
1
10
10²
10³
10⁴
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹

Reference # : B16

Authors : John F. Ready

Citation: "Laser-produced shocks and their relation to material damage", IEEE Journal of Quantum Electronics 14, 79 (1978)

Institution: Honeywell Corporate Material Sciences Center, Bloomington MN

Experimental Conditions:

Laser: TEA CO_2

Wavelength: 10.6 μm

Pulse energy: 2 J

Pulse duration: 100 ns fwhm plus 3-μs tail if N_2 included in gas mix

Intensity range: to $3x10^8$ W/cm^2

Atmosphere: 1 atm air to vacuum (0.01 Torr)

Spot dimensions: variable, never explicitly specified, and not uniquely determinable from the information given. The diameters will be several mm.

Target materials: Steel, aluminum, potassium chloride

Target dimensions: Not given

Measured quantities: pressure

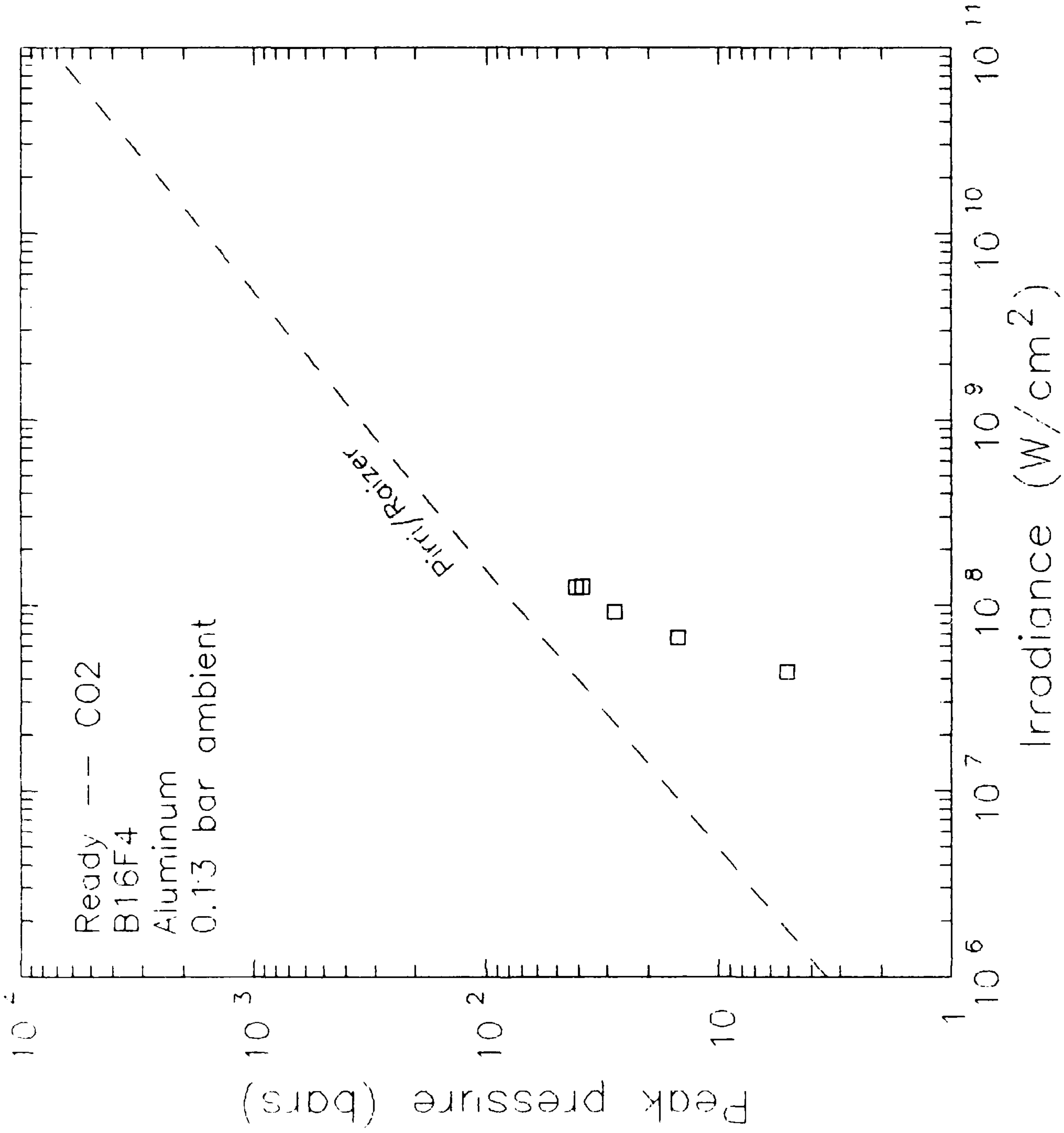
Measurement technique: rear-surface interferometry. "In addition measurements made as a function of target thickness indicate that the peak shock pressure is attenuated by approximately 20 percent in transmission through 0.6-mm inches (sic) of target material."

Figure caption: "Peak shock pressure as a function of laser power density for an aluminum target irradiated under the indicated conditions." "Peak shock pressure as a function of laser power density for potassium chloride."

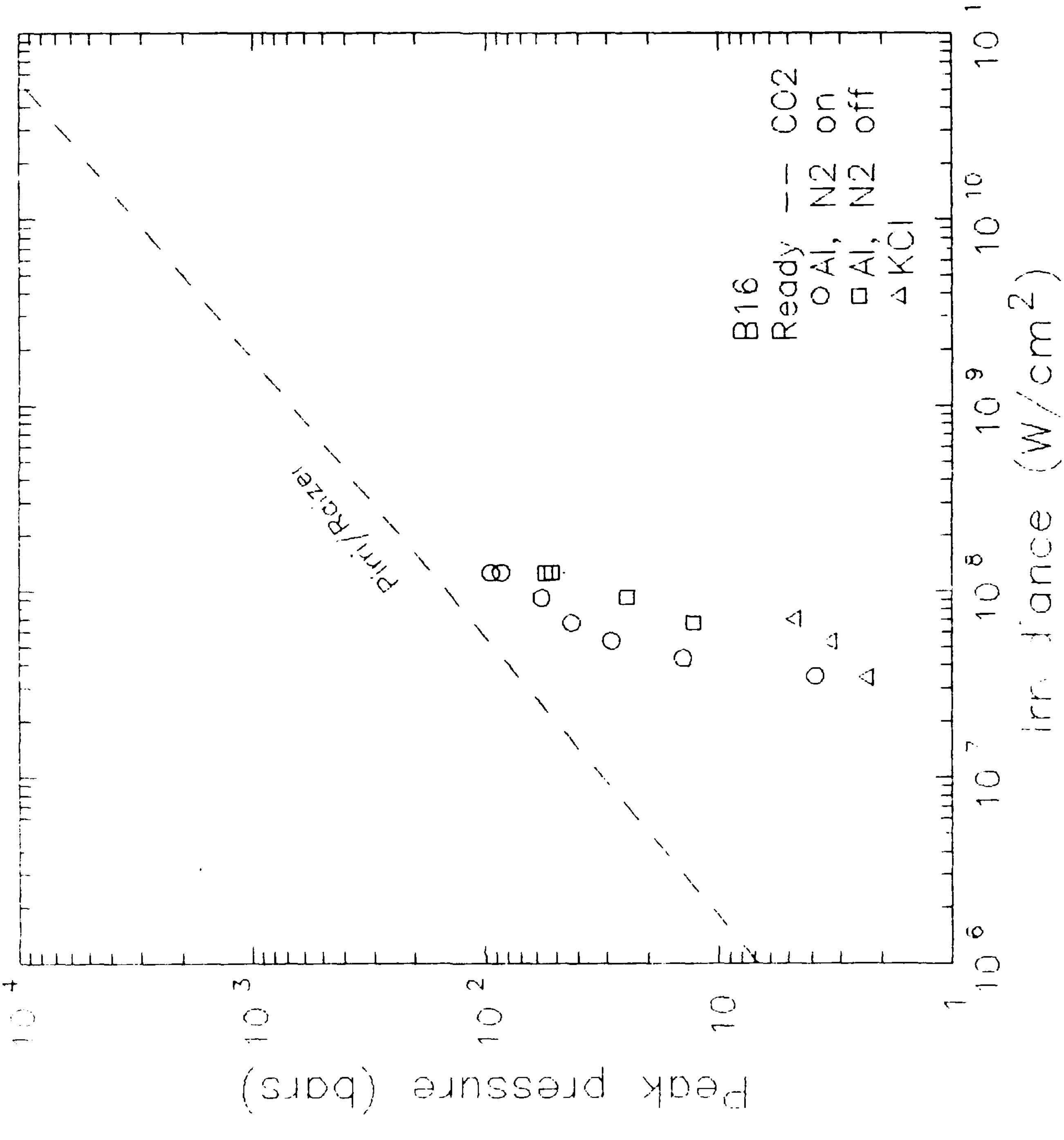
Comments: The measured peak pressures, even with a 20% adjustment for attenuation in the target thickness, are well below the Raizer-Pirri line and show a stronger intensity dependence than the LSD theory. This can be attributed to incomplete LSD formation with these short pulses. The "N_2 on" data lie well above the "N_2 off" values due to the more complete plasma formation, but remain below the Raizer-Pirri line due to the lower time-average laser intensity driving the LSD.

The results at reduced atmospheric pressure (100 Torr) are similar.

"The values of peak shock pressure (for KCl) are considerably lower than those that would have been observed for metallic samples under the same conditions of irradiation." This is clearly due to the low absorption of this infrared-transparent window material.



Ready -- CO2
B16F4
Aluminum
0.13 bar ambient
Pirri/Raizer
Peak pressure (bars)
Irradiance (W/cm^2)



Peak pressure (bars)
Irradiance (W/cm^2)
Pirri/Raizel
B16
Ready —— CO2
○ Al, N2 on
□ Al, N2 off
△ KCl

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Reference # : A05-1

Authors : B.S. Holmes

Citation: "Pulsed laser thermal mechanical damage study", AFWL-TR-80-31, Vol. 1 (of 3), (June 1981)

Institution: Stanford Research Institute, Menlo Park CA

Experimental Conditions:

Laser: electron-beam-pumped CO_2 (Avco "Driver")

Wavelength: 10.6 μm

Pulse energy: 0.7 - 3.34 kJ

Pulse duration: 7 - 20 μs; high-intensity leading spike

Intensity range: 1 - 10 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: 22.5, 30, 68 cm^2

Target materials: Pyroceram, slip-cast fused silica (SCFS), Cordopreg, fiberglass

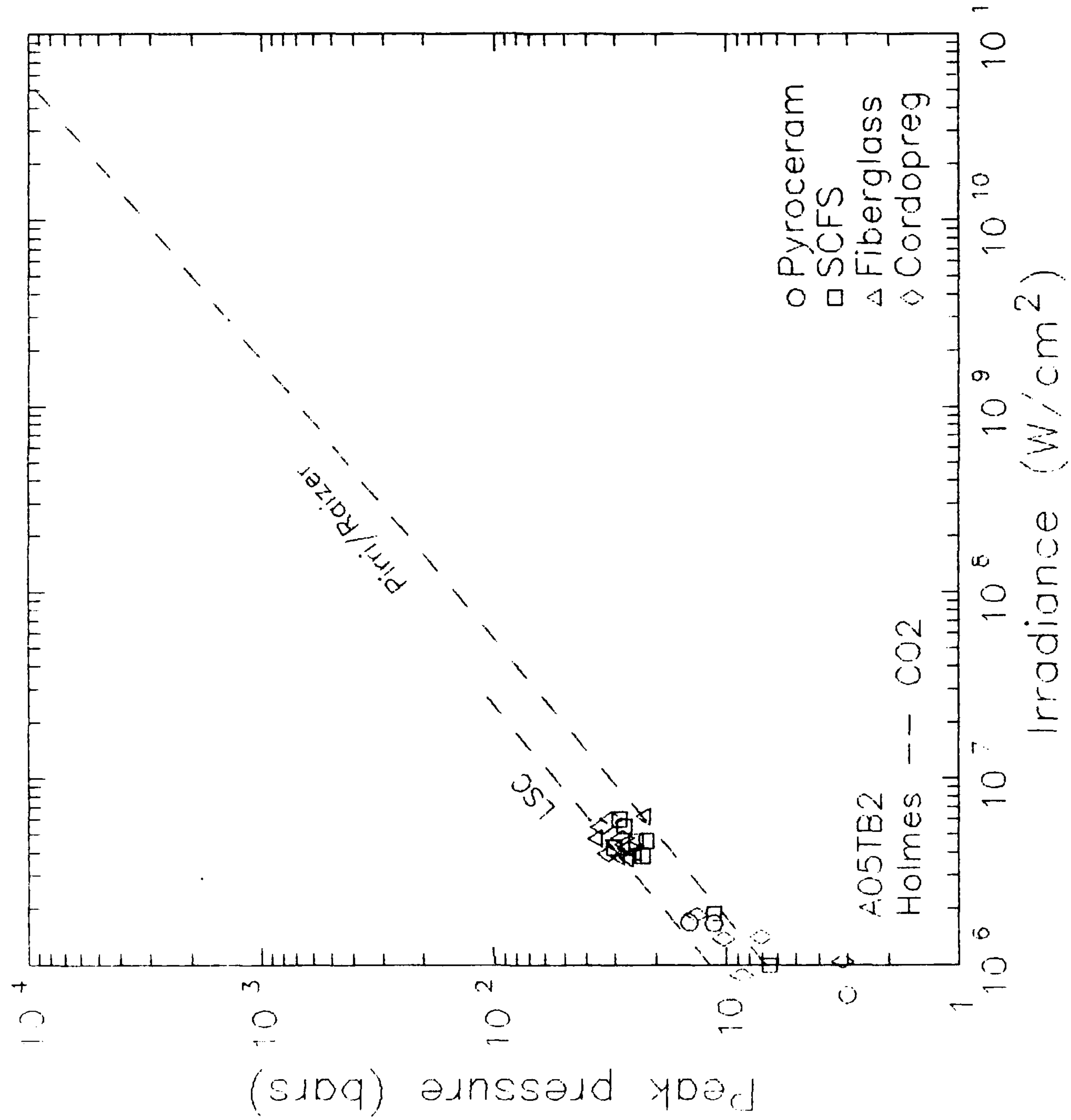
Target dimensions:

Measured quantities: pressure

Measurement technique(s): carbon (Dynasen) piezoresistive gauges, 0.6x1.2 cm, and ytterbium (SRI) piezoresistive gauges, 2.5x2.5 cm

Table caption: "Driver laser surface pressure measurements"

Comments: "The lack of dependence of peak pressure on target material is evidence that surface pressure in these experiments was produced solely by plasma formation on the target. Peak pressure in the plasma depends primarily on flux and is readily predicted using existing theories of plasma formatic hese experiments feature very large spots and low plasma dimensi ity.



Pyroceram
SCFS
Fiberglass
Cordopreg
Pirri/Raizer
LSC
A05TB2
Holmes — CO2
Irradiance (W/cm^2)
Peak pressure (bars)

Reference # : A06

Authors : T.R. Tucker and L.R. Hettche

Citation: "Pressure coupling of pulsed high-energy CO_2 laser irradiation to aluminum targets", unpublished, undated (ca. 1977).

Institution: Naval Research Laboratory, Washington DC

Experimental Conditions:

Laser: electron-beam-pumped, sustained-discharge CO_2 (Avco Thumper)
Wavelength: 10.6 μm
Pulse energy: 5 - 18 kJ
Pulse duration: 20 or 45 μs plateau, leading gain-switched spike

Intensity range: 2 - 8 MW/cm^2
Atmosphere: 1 atm air

Spot dimensions: 63 to 136 cm^2 (annular laser beam separated into segments and individually directed to produce roughly circular spot)

Target materials: aluminum

Target dimensions: 36 cm diameter

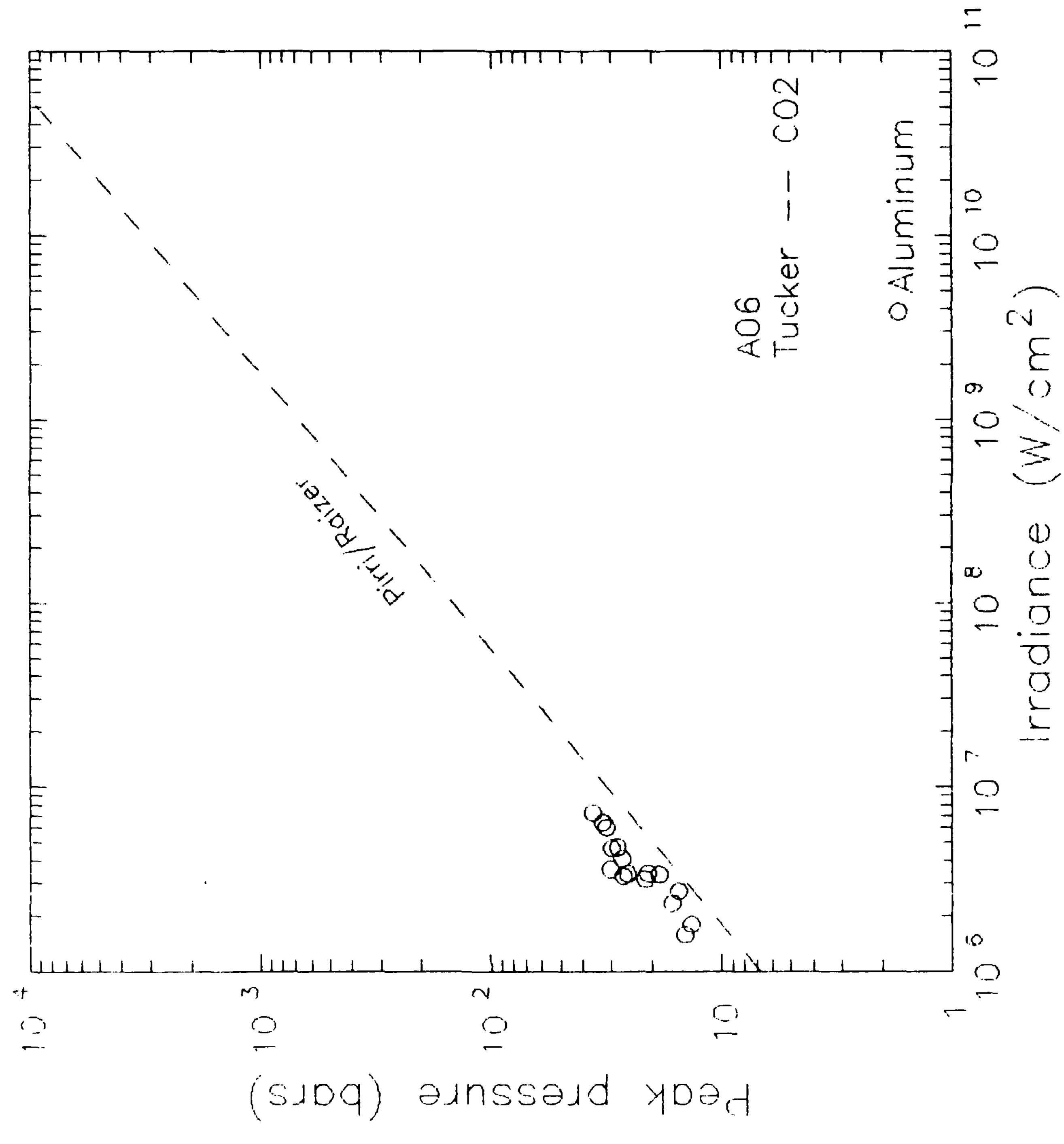
Measured quantities: pressure

Measurement technique: charge-mode quartz (Kistler) piezoelectric gauges

Figure caption: "Plateau pressure behind the gain spike as a function of spatially averaged incident flux is compared to theoretical calculations for LSD and LSC waves."

Comments: "In agreement with previous data of small beam area experiments, the 2/3 power dependence of pressure on incident intensity seems to be obeyed, but the nature of the laser absorption wave is not solely detonation or combustion. The actual plasma is a mixture of the expanding spherical and cylindrical models."

These pressure data lie modestly above the Pirri-Raizer line. This is attributed to the transition to a combustion propagation mode at these low laser intensities. The wave propagates by thermal conduction, a slower mode than detonation, prevailing here because the shock is too weak to make the air behind the shock opaque to the laser irradiation. The slower propagation yields a higher pressure.


A06
Tucker --- CO2
o Aluminum
Pirri/Raizer
Peak pressure (bars)
Irradiance (W/cm²)
1
10
10²
10³
10⁴
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹

Reference # : B1

Authors : D. Dufresne, Ph. Bournot, J.P. Caressa, G. Bosca, and J. David

Citation: "Pressure and impulse on an aluminum target from pulsed laser irradiation at reduced ambient pressure", Appl. Phys. Lett. 38, 234-236 (1981)

Institution: Institut de Mecanique des Fluides de Marseille, Marseille, France; C.E.A. Limeil-Service H.D.E., St. Georges, France

Experimental Conditions:

Laser: TEA CO_2

Wavelength: 10.6 μm

Pulse energy: to 200 J

Pulse duration: 50 ns spike; 2.5 μs N2 tail, depending on gas mix

Intensity range: 1.5e8 W/cm² (spike), 3.5e7 W/cm² (tail)

Atmosphere: air, 1 atm to vacuum (1.5 Torr)

Spot dimensions: 1.5 cm diameter

Target materials: aluminum

Target dimensions: 6 cm diameter, 0.1 cm thick

Measured quantities: pressure

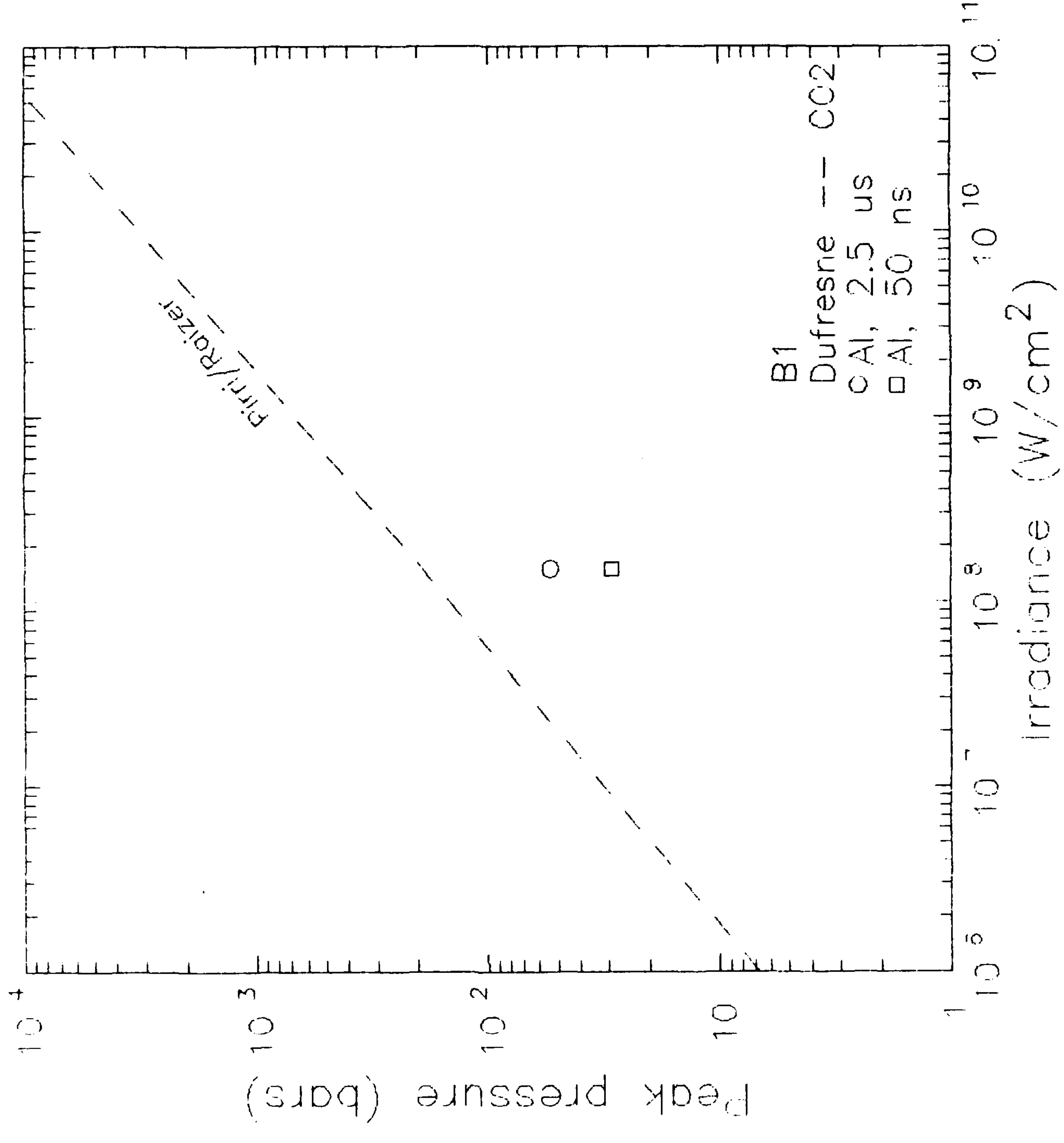
Measurement technique: carbon (Dynasen) piezoresistive gauges, 1.27x0.635 mm

Figure caption: "Pressure on the target vs. [ambient pressure]"

Comments: The peak pressure is little affected by the presence of the low-power pulse tail, indicating dominance of high-power spike for this particular pulse shape. Transition from air-plasma behavior to vacuum behavior is gradual, rather than abrupt, over the range 10-200 Torr. The dependence on ambient pressure is wholly different from the prediction of the Pirri-Raizer theory.

Specific impulse values were obtained by integration (presumably numerical, though this is not specified) of the pressure-time data.

The one-atmosphere data were extracted from the plot of peak pressure versus ambient pressure for comparison with other 1 atm data.


Peak pressure (bars)
Irradiance (W/cm^2)
Pirri/Raizer
B1
Dufresne — CC2
○ Al, 2.5 us
□ Al, 50 ns
1
10
10^2
10^3
10^4
10^6
10^7
10^8
10^9
10^{10}
10^{11}

Reference # : A05-2

Authors : B.S. Holmes

Citation: "Pulsed laser thermal mechanical damage study", AFWL-TR-80-31, Vol. 1 (of 3), (June 1981)

Institution: Stanford Research Institute, Menlo Park CA

Experimental Conditions:

Laser: 50-liter photo-initiated pulsed DF (Boeing PHOCL-50)

Wavelength: 3.8 μm

Pulse energy: 500-600 J

Pulse duration: 7 μs total (triangular pulse)

Intensity range: 7 - 37 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: 56% of beam energy in square 2 cm x 2 cm

Target materials: 2024-T3 aluminum, 6Al-4V titanium, fiberglass

Target dimensions:

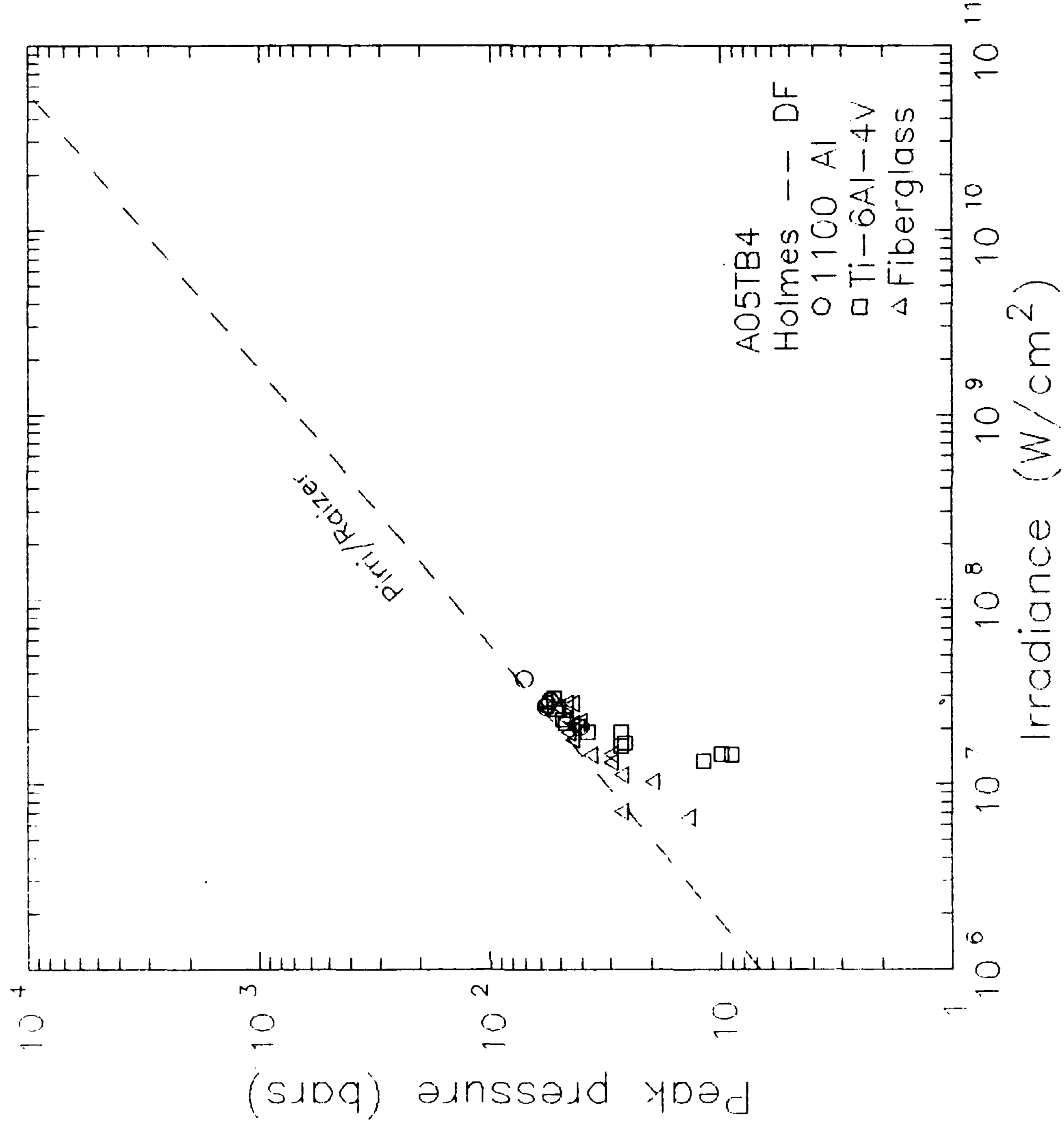
Measured quantities: pressure (target stress)

Measurement technique: carbon (Dynasen) piezoresistive gauges, 0.15x0.15 cm

Table caption: "Results of surface pressure measurements"

Comments: "The PHOCL-50 laser experiments more clearly showed the effects of delayed plasma ignition since plasam often was not formed in these experiments until several microseconds after the start of lasing."

This experiment highlights the difficulty of evaluating experiments with very non-ideal pulse shapes and spatial distributions. The data are shown here as a function of the peak laser irradiance, but Holmes found more favorable comparisons with theory by plotting peak pressure versus the maximum laser irradiance after ignition.



Pirri/Raizer
A05TB4
Holmes — — DF
○ 1100 Al
□ Ti−6Al−4V
△ Fiberglass
Peak pressure (bars)
Irradiance (W/cm²)
1
10
10²
10³
10⁴
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹

Reference # : B33

Authors : L.R. Hettche, T.R. Tucker, J.T. Schriempf, R.L. Stegman, and S.A. Metz

Citation: "Mechanical response and thermal coupling of metallic targets to high-intensity 1.06μ laser radiation", J. Appl. Phys. 47, 1415-1421 (1976)

Institution: Naval Research Laboratory

Experimental Conditions:

Laser: five-stage Nd:glass
- Wavelength: 1.06 μm
- Pulse energy: 125 J
- Pulse duration: 1-100 μs

Intensity range: 20 - 600 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: 0.25 cm^2 (0.56 cm diam)

Target materials: 1100 Al, Ti-6Al-4V

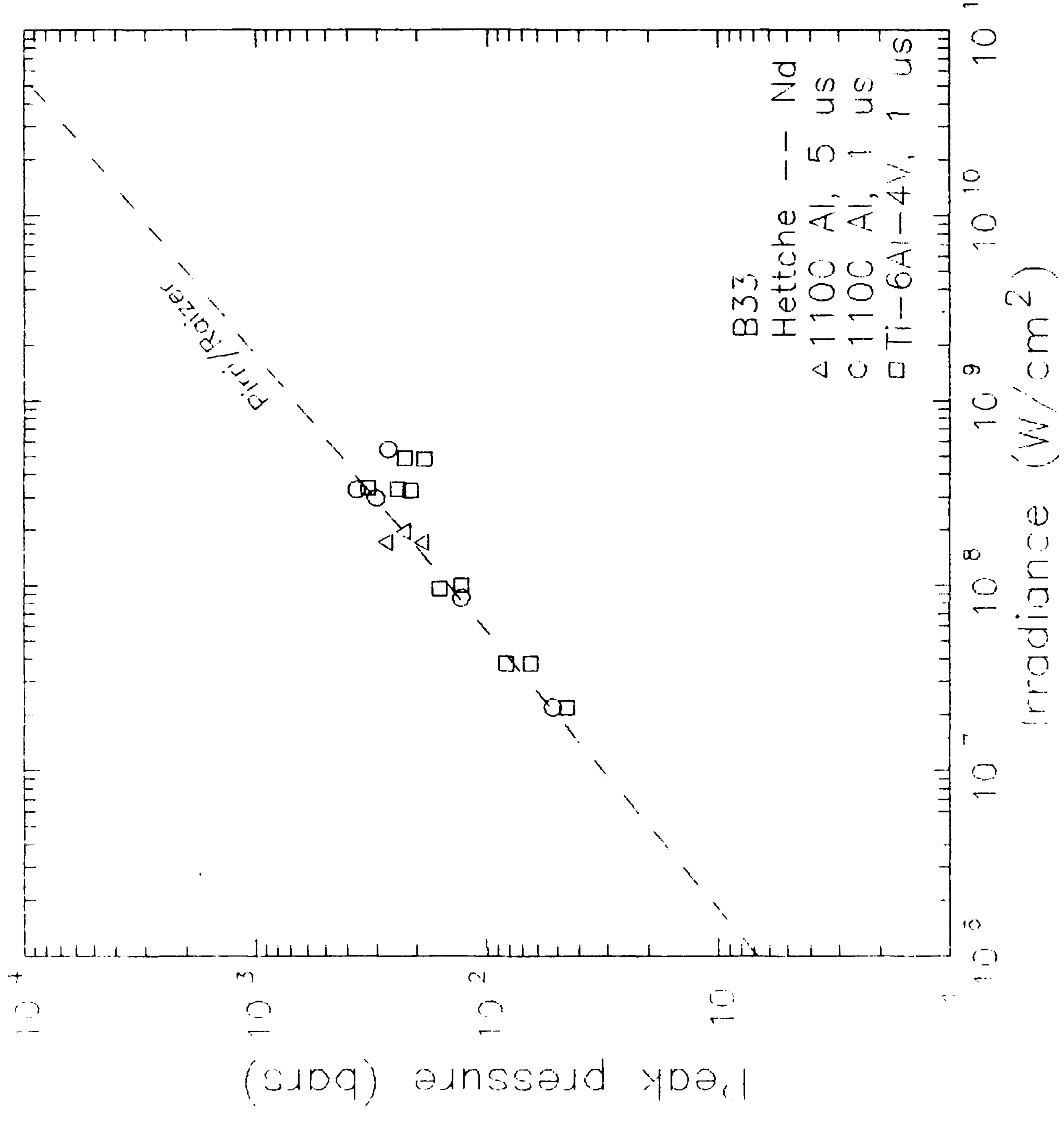
Target dimensions: 5 cm diameter, 0.25 mm (Al) or 1.0 mm (Ti) thick

Measured quantities: peak pressure

Measurement technique: rear-surface interferometry through 10 cm quartz rod

Figure caption: "Peak pressure in metallic targets is plotted vs the spatially averaged temporally peaked laser power density. Circles represent Al targets; the triangles are Ti. The LSD wave threshold intensity is reported to be about 1x10^8 W/cm^2."

Comments: These data are indistinguishable from the Boiko observations (B17), despite the difference in wavelength. The Raizer-Pirri theory describes the peak pressure very accurately.



B33
Hettche -- Nd
△ 1100 Al, 5 us
○ 1100C Al, 1 us
□ Ti-6Al-4V, 1 us
Pirri/Raizer
Irradiance (W/cm^2)
Peak pressure (bars)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10
10^2
10^3
10^4

Reference # : ETI

Authors : Hartley H. King, Kirk A. Ludwig, and Thomas L. Menna

Citation: "Measurements of stresses induced in targets by a 30 nsec 1.06 micron laser pulse in air", General Research Corp. Rept. CR83-1182 (August 1983)

Institution: Effects Technology Inc. division of the General Research Corporation

Experimental Conditions:

Laser: four-stage Nd:glass (Battelle-Columbus)

Wavelength: 1.06 μm

Pulse energy: to 1 kJ

Pulse duration: 30 ns fwhm

Intensity range: 2×10^{9} - $2x^{10}$ W/cm^2

Atmosphere: air, 1 atm

Spot dimensions: 1 cm diam

Target materials: aluminum, carbon (Grafoil, rolled graphite)

Target dimensions: large compared to laser spot

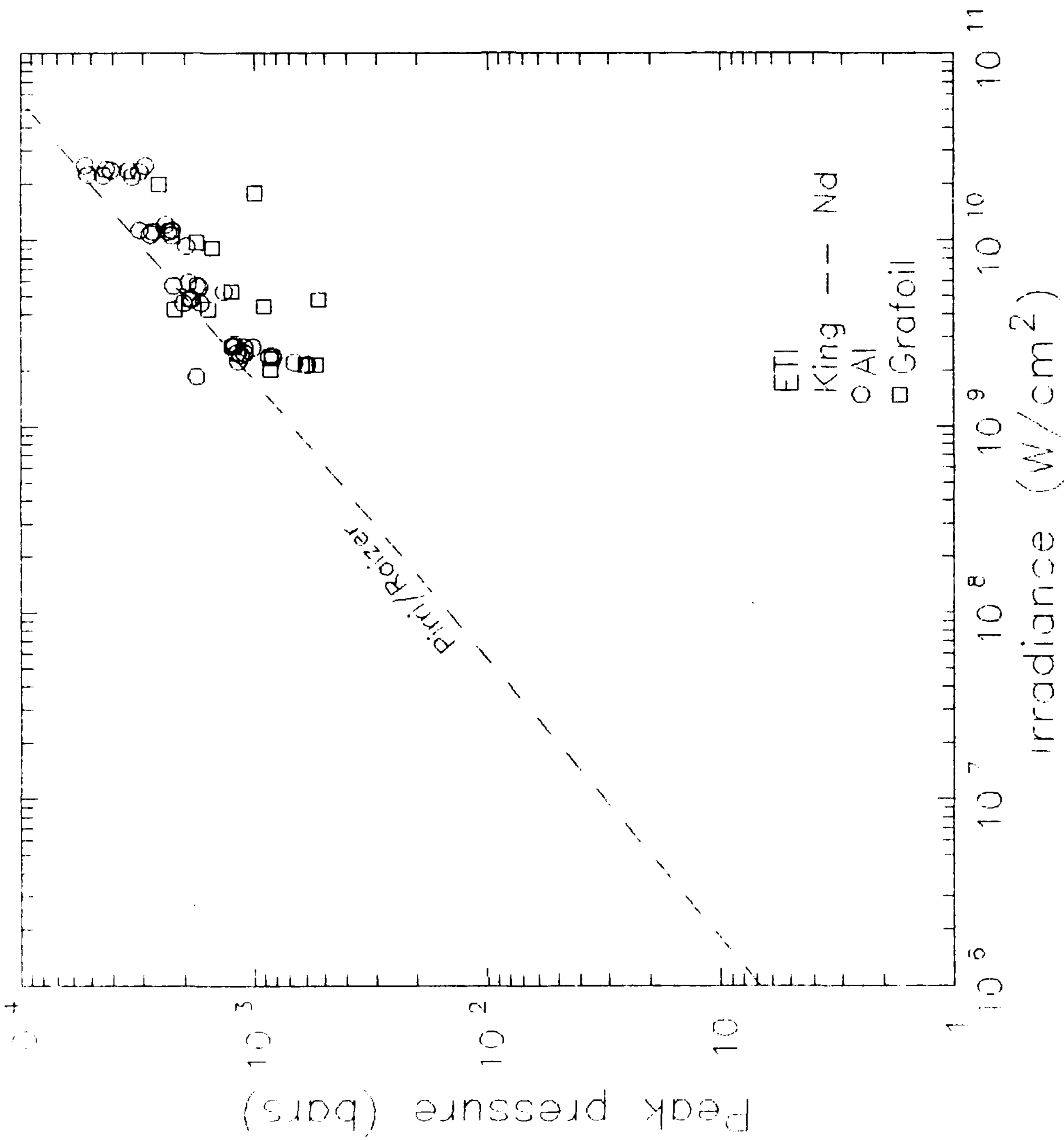
Measured quantities: pressure

Measurement technique(s): carbon (Dynasen) piezoresistive stress gauges; rear-surface interferometry

Table caption: "Peak stresses for aluminum target shots"; "peak stresses for Grafoil target shots"

Comments: The distortion in the stress-wave shapes due to sensor depth within the targets was corrected for by propagation analysis. This extrapolation increased the final surface-stress values by about 10%.

These peak-pressure data lie somewhat below the Pirri-Raizer LSD line. The difference is attributed to the formation of an absorption wave propagating by ultraviolet radiation, the thermal emission from the extremely hot plasma in the vacuum ultraviolet being sufficient to heat the air to laser opacity. For these very high laser intensities, the radiation propagation mechanism displaces detonation-wave propagation. The higher propagation speed leads to a lower peak pressure.



Peak pressure (bars)
Irradiance (W/cm^2)
Piri/Raizer
ETI
King — — Nd
○ Al
□ Grafoil

Reference # : T3

Authors : Bayard S. Holmes

Citation: "Assessment of the vulnerability and lethality of aerospace systems, volume II: laser coupling measurements", Technical Report DNA-TR-85-000, May 1986

Institution: SRI International, Menlo Park CA

Experimental Conditions:

Laser: four-stage Nd:glass (Battelle-Columbus)

Wavelength: 1.06 μm

Pulse energy: to 1 kJ

Pulse duration: 30 ns fwhm

Intensity range: $2x10^9$ - $2x10^{10}$ W/cm^2

Atmosphere: air, 1 atm

Spot dimensions: 1 cm diam

Target materials: aluminum, carbon (Grafoil, rolled graphite)

Target dimensions: large compared to laser spot

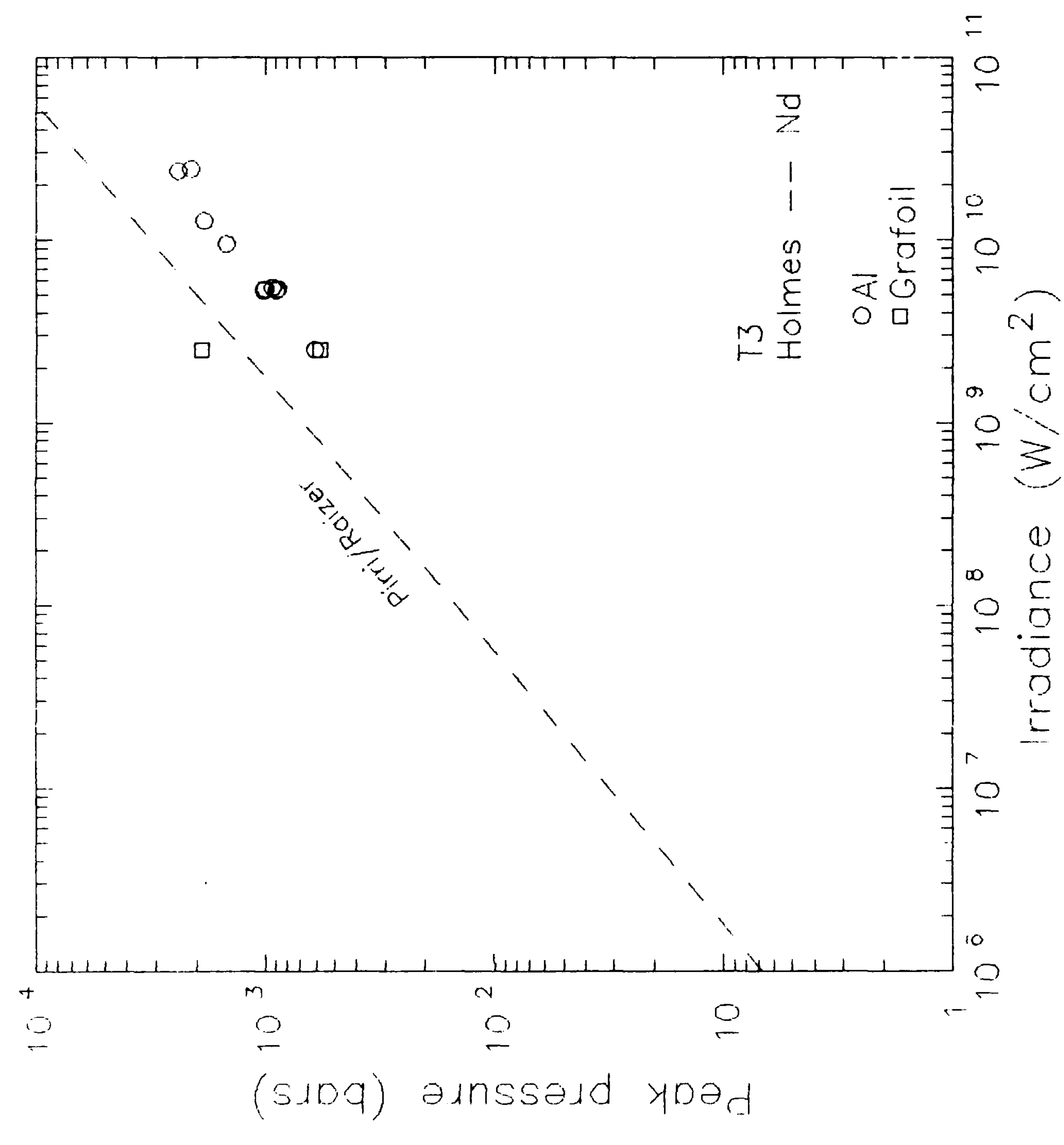
Measured quantities: pressure

Measurement technique(s): carbon and ytterbium piezoresistive stress gauges

Figure caption:

Comments: These data were obtained in the same experimental run as the preceding entry (ETI), and are essentially identical. The same analysis applies:

These peak-pressure data lie somewhat below the Pirri-Raizer LSD line. The difference is attributed to the formation of an absorption wave propagating by ultraviolet radiation, the thermal emission from the extremely hot plasma in the vacuum ultraviolet being sufficient to heat the air to laser opacity. For these very high laser intensities, the radiation propagation mechanism displaces detonation-wave propagation. The higher propagation speed leads to a lower peak pressure.


T3
Holmes --- Nd
○ Al
□ Grafoil
Pirri/Raizer
Peak pressure (bars)
Irradiance (W/cm^2)
1
10
10^2
10^3
10^4
10^6
10^7
10^8
10^9
10^{10}
10^{11}

PRESSURE DATA IN AIR (REDUCED PRESSURE/DENSITY)

#	1st author	yr	wavel	matls
B13	Beverly	1976	10.6	Aluminum, PMMA, cellulose acetate
B17	Boiko	1977	10.6	Aluminum, lead, titanium
B16	Ready	1978	10.6	Steel, aluminum, potassium chloride
B1	Dufresne	1981	10.6	Aluminum

PRESSURE (STRESS) DATA AT REDUCED AIR DENSITY

Only a few works have been found with pressure (target stress) measurements made at reduced ambient air density, despite the obvious interest in the consequences of interaction at high altitude. Two effects should be evident: first, at air densities close to one atmosphere, the peak pressure should decrease, according to the Pirri/Raizer model; second, at some low density, the air should become so dilute that it is no longer rendered opaque by the shock, and the interaction should change to that of the vacuum interaction.

The Pirri/Raizer model predicts a peak pressure varying as the cube root of the ambient density. Because the model works very well at normal density, there should be good confidence in this prediction. In fact, as the very limited data here show, there is no good confirmation of this predicted behavior.

At some quite unpredictable ambient density, presumably dependent on both wavelength and laser irradiance, the Pirri/Raizer model should fail altogether and a vacuum-type interaction appear. This transition is very clear in thermal coupling work, and appears at an ambient density of 3×10^{-3} bars for CO_2 laser irradiation of aluminum [1]. Some of the observations here, by Walters at Battelle-Columbus, are consistent with this result; others, e.g. the Dufresne data, are not. The density, or altitude, dependence of the air-vacuum transition is nearly unexplored territory.

[1] J.A. McKay and J.T. Schriempf, "Pulsed CO_2 lasers for the surface heating and melting of metals", IEEE Journal of Quantum Electronics QE-17, 2008 (1981).

Reference # : B13

Authors : R. E. Beverly, III, and C. T. Walters

Citation: "Measurement of CO_2-laser-induced shocks above and below LSD-wave thresholds", J. Appl. Phys. 47, 3485-3495 (1976)

Institution: Battelle Columbus Laboratories, Columbus OH

Experimental Conditions:
- Laser: TEA CO_2
  - Wavelength: 10.6 μm
  - Pulse energy: 80 J
  - Pulse duration: 80 ns fwhm plus "several microseconds" N_2 tail
- Intensity range: 32 - 580 MW/cm2 (varied with attenuators)
- Atmosphere: 1 atm air to vacuum (1×10^{-7} Torr)

Spot dimensions: 0.61 cm diameter (0.29 cm^2 area) (fixed)

Target materials: Aluminum, PMMA, cellulose acetate

Target dimensions: 5 cm diameter (carbon gauge specimens); 0.7, 1.14 cm diameter (quartz gauge specimens)

Measured quantities: pressure

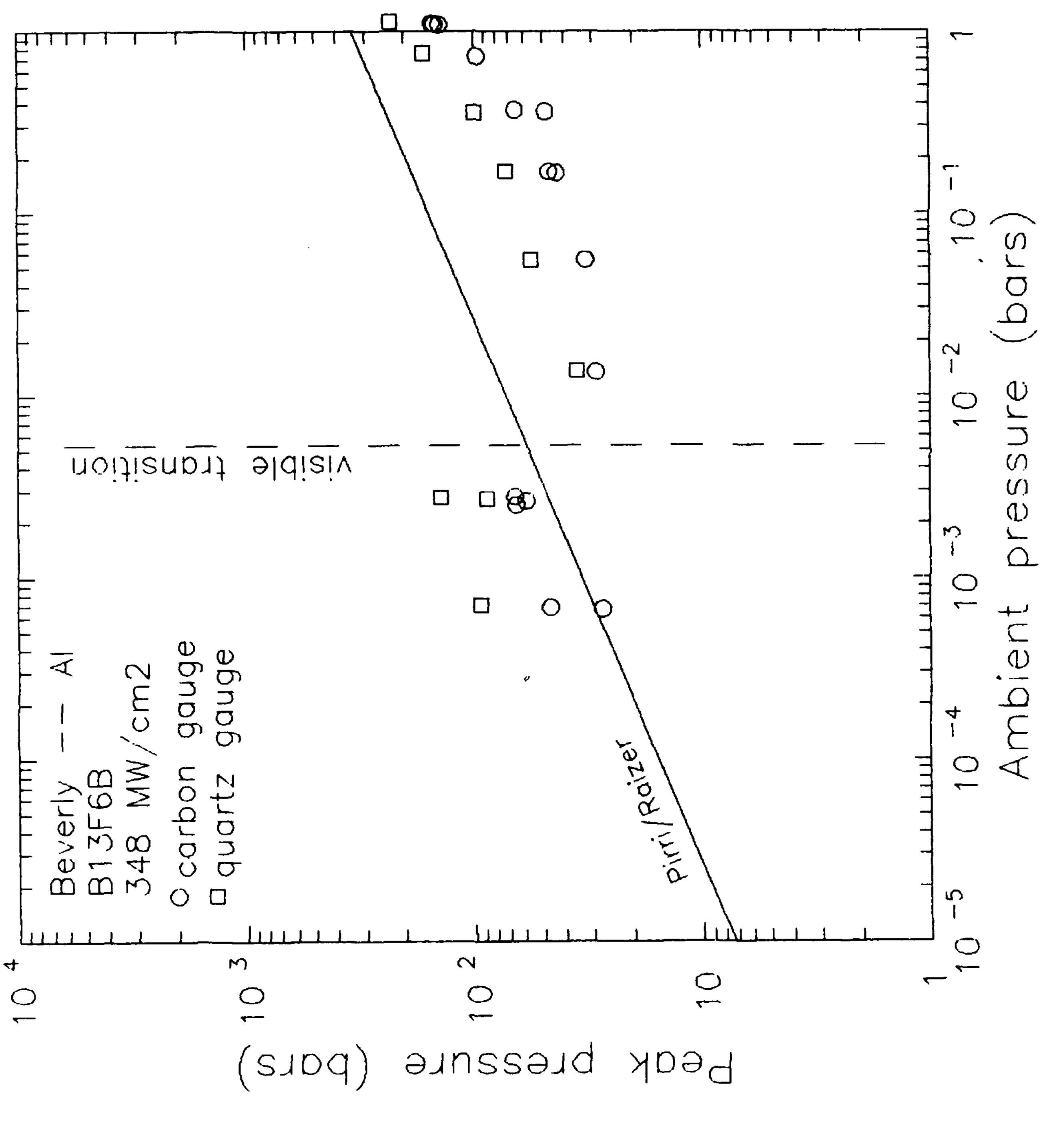
Measurement technique(s): (1) quartz piezoelectric (Sandia type, shorted), 0.318 cm active diameter, 0.127 cm length (220 ns writing time); silicone grease bond to target; (2) carbon piezoresistive (Dynasen), 0.13x0.15x0.0036 cm; epoxied onto front face of 3.2 cm thick backup disk, then epoxied or silicone-bonded to target disk, yielding an embedded gauge

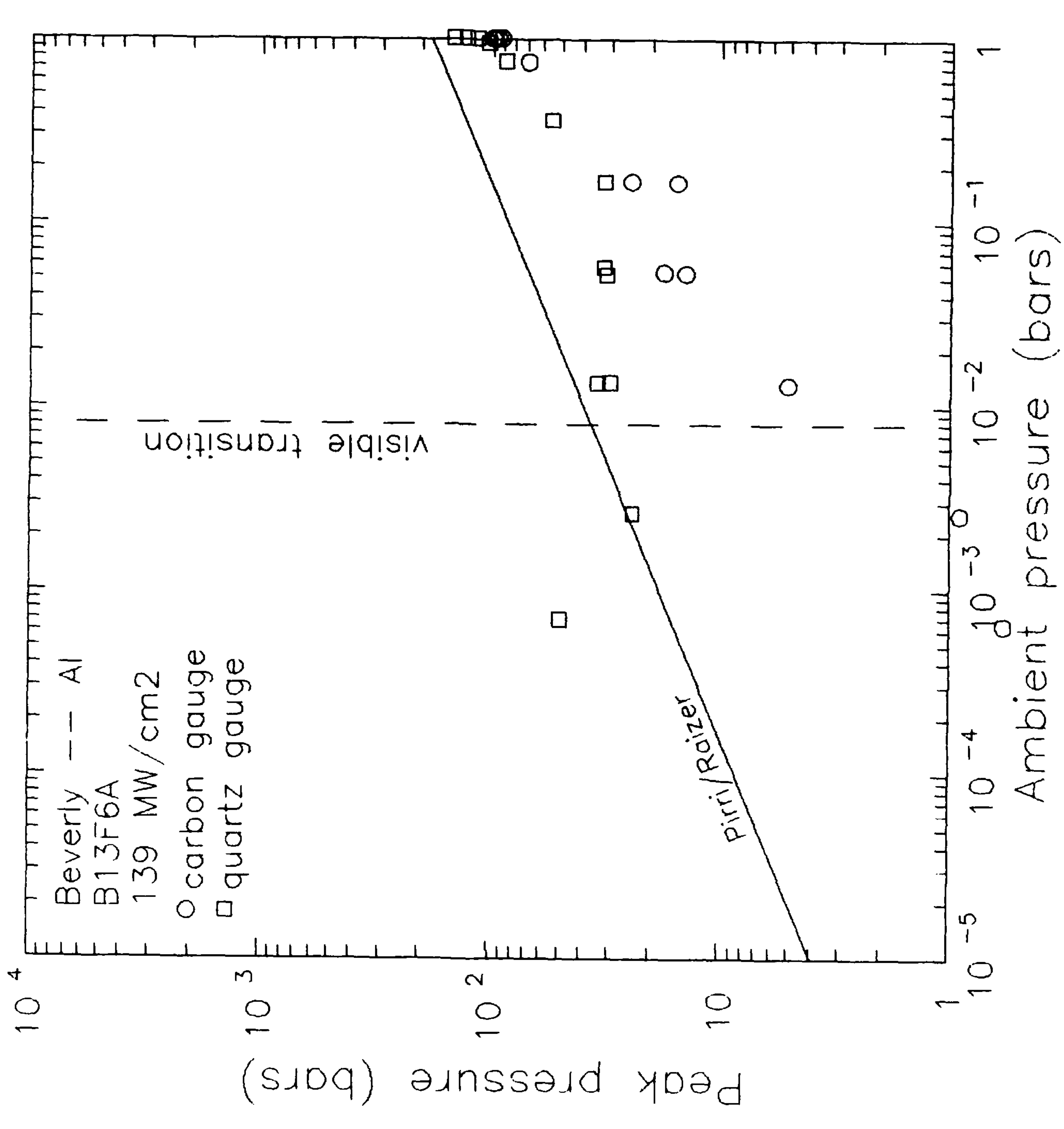
Figure captions: Fig. 6: "Peak shock pressures in aluminum as a function of ambient pressure for [peak laser irradiance] (a) 1.39×10^8 W/cm^2 and (b) 3.48×10^8 W/cm^2. Experimental data are shown for both quartz and carbon gauge measurements. . ." Fig. 10: "Peak shock pressures in cellulose acetate and PMMA as a function of ambient pressure for [peak laser irradiance] (a) 1.39×10^8 W/cm^2 and (b) 3.48×10^8 W/cm^2. Experimental data are shown for both quartz and carbon gauge measurements. . ."

Comments: As observed by Ready under similar conditions, the peak pressures on aluminum lie significantly below the Pirri-Raizer values, but show the same cube-root dependence above about 0.1 bar ambient. Below this pressure the peak pressures are constant or increase moderately, indicating the existence of a vacuum ablation interaction instead of the air plasma interaction.

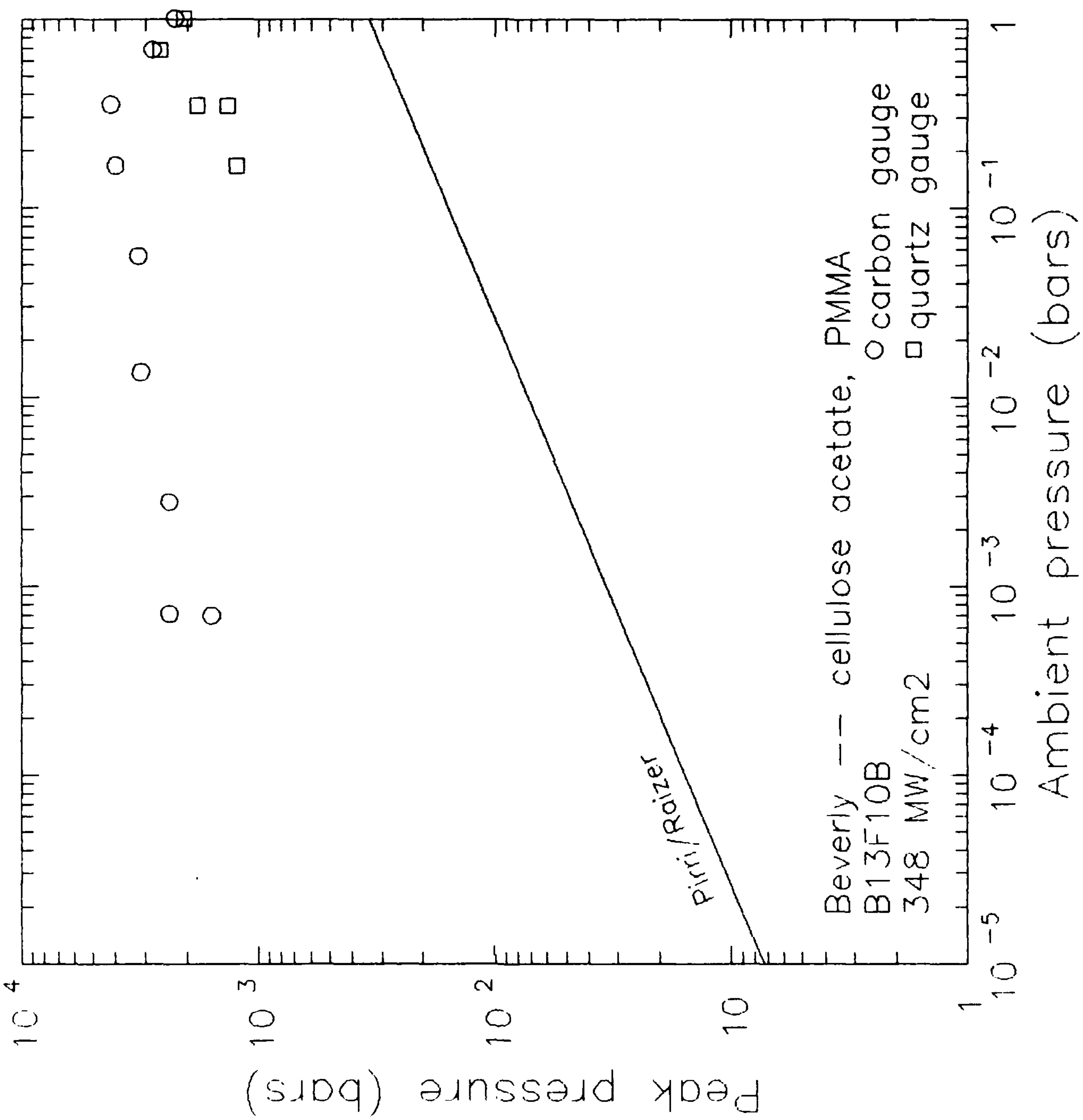
The pressures observed on the nonmetals are well above the Pirri-Raizer air-plasma line, and show little ambient pressure dependence, as expected for an interaction which is essentially material ablation.

A visible transition in the nature of the plasma was evident from open-shutter photography, and is indicated on the plots.

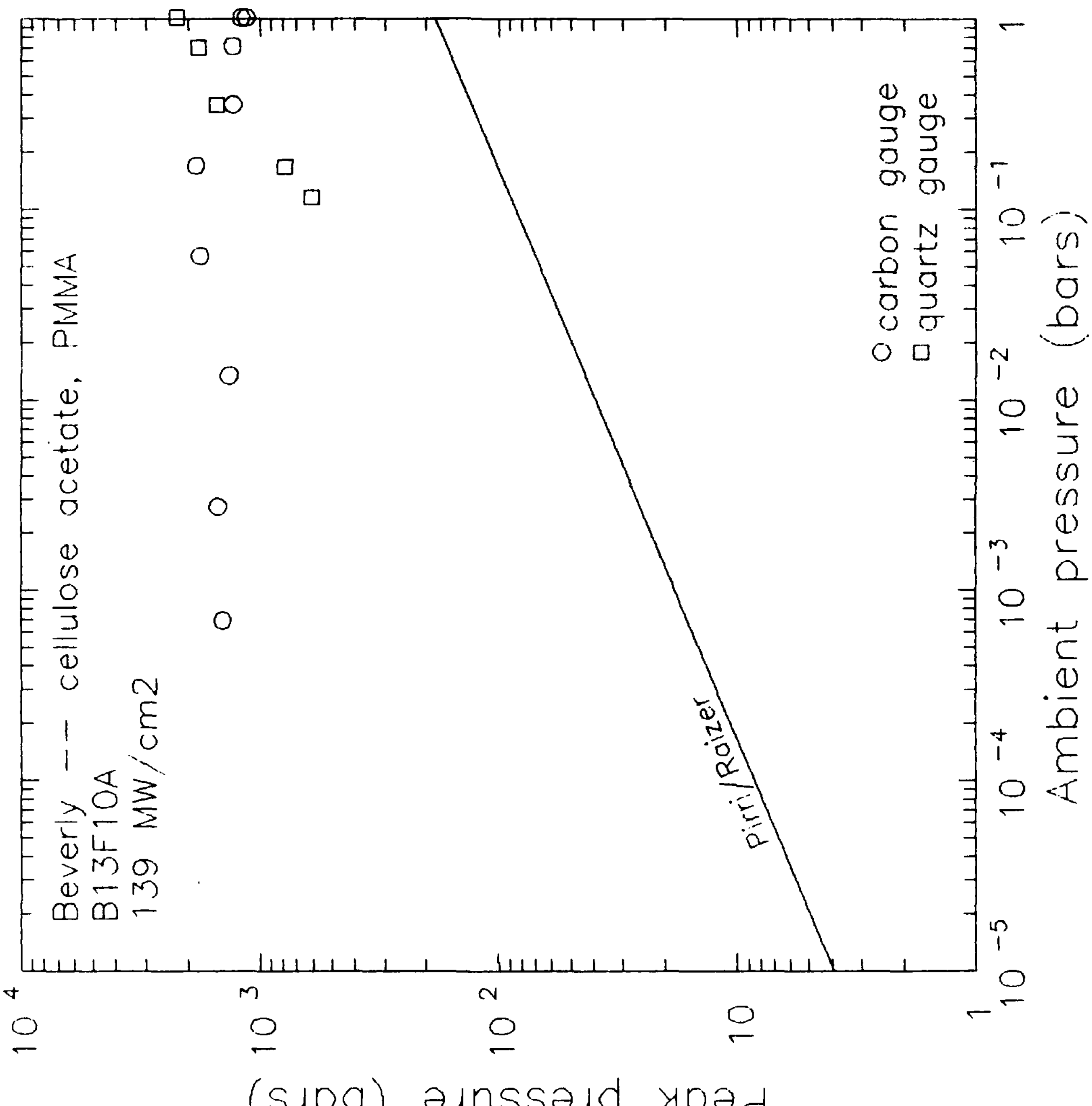

Beverly — Al
B13F6B
348 MW/cm2
carbon gauge
quartz gauge
Pirri/Raizer
visible transition
Peak pressure (bars)
10^4
10^3
10^2
10
1
Ambient pressure (bars)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1



Beverly — Al
B13F6A
139 MW/cm2
○ carbon gauge
□ quartz gauge
Pirri/Raizer
visible transition
Peak pressure (bars)
Ambient pressure (bars)
10^4
10^3
10^2
10
1
10^-5
10^-4
10^-3
10^-2
10^-1
1



Beverly — cellulose acetate, PMMA
B13F10B
348 MW/cm2
○ carbon gauge
□ quartz gauge
Pirri/Raizer
Peak pressure (bars)
Ambient pressure (bars)


Beverly -- cellulose acetate, PMMA
B13F10A
139 MW/cm2
Pirri/Raizer
○ carbon gauge
□ quartz gauge
Peak pressure (bars)
Ambient pressure (bars)
10^{4}
10^{3}
10^{2}
10
1
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

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Reference # : B17

Authors : V.A. Boiko, V.A. Danilychev, B.N. Duvanov, V.D. Zvorykin, I.V. Kholin, and A. Yu. Chugunov

Citation: "Measurement of gasdynamic pressure on a target subjected to CO_2 laser radiation", Sov. J. Quantum Electron. 7, 465-468 (1977)

Institution: P.N. Lebedev Physics Institute, Moscow

Experimental Conditions:
- Laser: e-beam CO_2
  - Wavelength: 10.6 μm
  - Pulse energy: 100 J
  - Pulse duration: 120 ns fwhm, 450 ns total.
- Intensity range: 1×10^7 - 1×10^9 W/cm^2
- Atmosphere: 1 atm to vacuum (0.07 Torr)

Spot dimensions: 0.5 - 3 cm^2

Target materials: Aluminum, lead, titanium

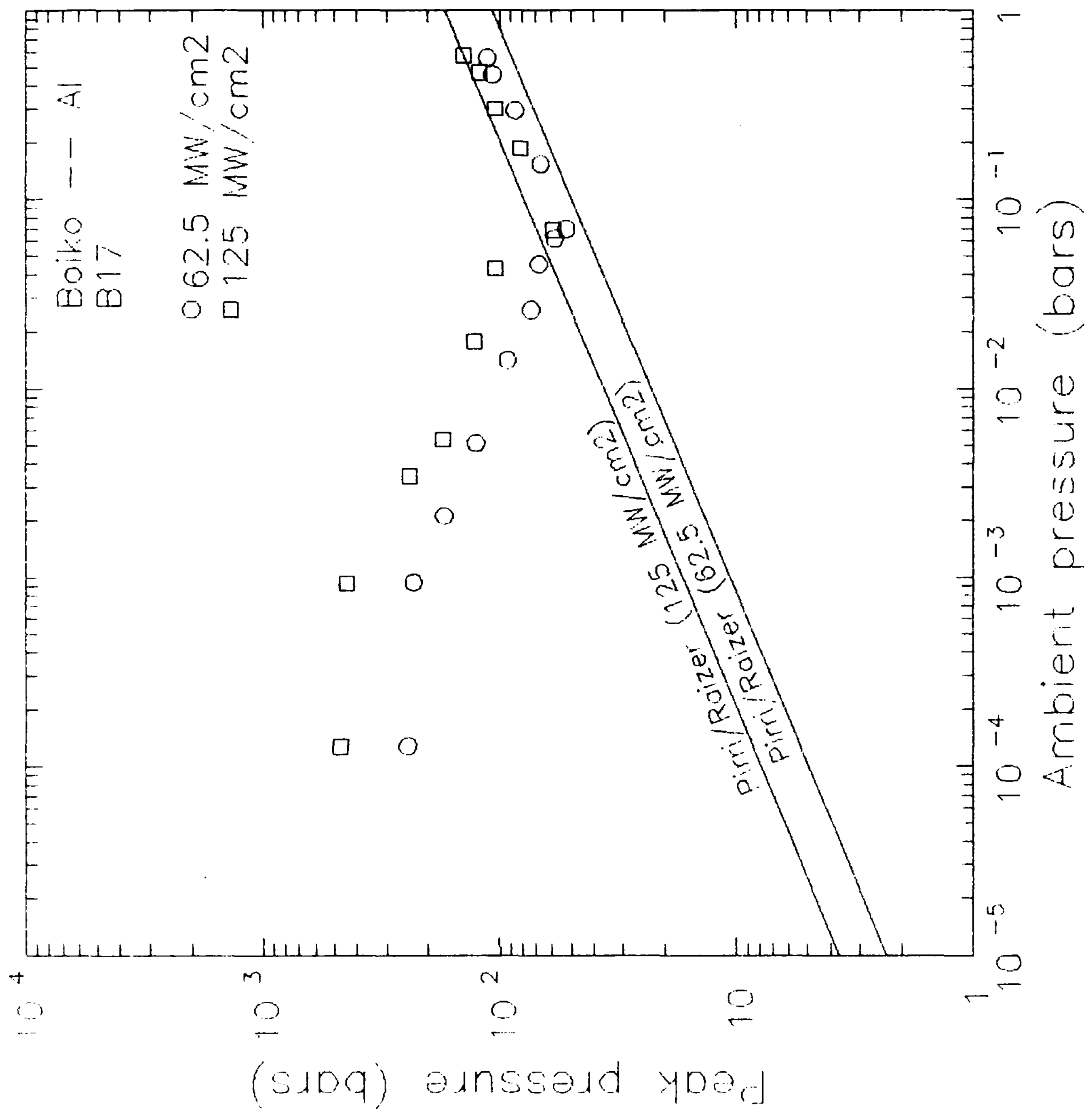
Target dimensions: 1 cm diameter foils, thickness 0.7 mm (Pb), 0.15 mm (Al), 0.05 mm (titanium).

Measured quantities: pressure

Measurement technique: quartz piezoelectric (Sandia type), 0.4 cm active diameter, 0.1 cm length (175 ns writing time); in "acoustic contact" with target specimens

Figure caption: "Dependences of the amplitude of the pressure on a target on the ambient pressure obtained for [laser fluence] 10 and 20 J/cm^2; [peak irradiance] 6.25×10^7 and 1.25×10^8 W/cm^2."

Comments: The pressure data near 1 atm follow the Pirri-Raizer formula nicely. Below about 0.06 bars, the pressure diverges sharply, increasing with decreasing ambient pressure. This shows clearly the onset of a vacuum-type plasma in place of the air plasma.



Boiko — Al
B17
○ 62.5 MW/cm2
□ 125 MW/cm2
Piri/Raizer (125 MW/cm2)
Piri/Raizer (62.5 MW/cm2)
Peak pressure (bars)
Ambient pressure (bars)

Reference # : B16

Authors : John F. Ready

Citation: "Laser-produced shocks and their relation to material damage", IEEE Journal of Quantum Electronics 14, 79-84 (1978)

Institution: Honeywell Corporate Material Sciences Center, Bloomington MN

Experimental Conditions:

Laser: TEA CO_2

Wavelength: 10.6 μm

Pulse energy: 2 J

Pulse duration: 100 ns fwhm plus 3-μs tail if N_2 included in gas mix

Intensity range: to 300 MW/cm2

Atmosphere: 1 atm air to vacuum (0.01 Torr)

Spot dimensions: variable, never explicitly specified, and not uniquely determinable from the information given. The diameters will be several mm.

Target dimensions: Not given

Target materials: Steel, aluminum, potassium chloride

Measured quantities: pressure

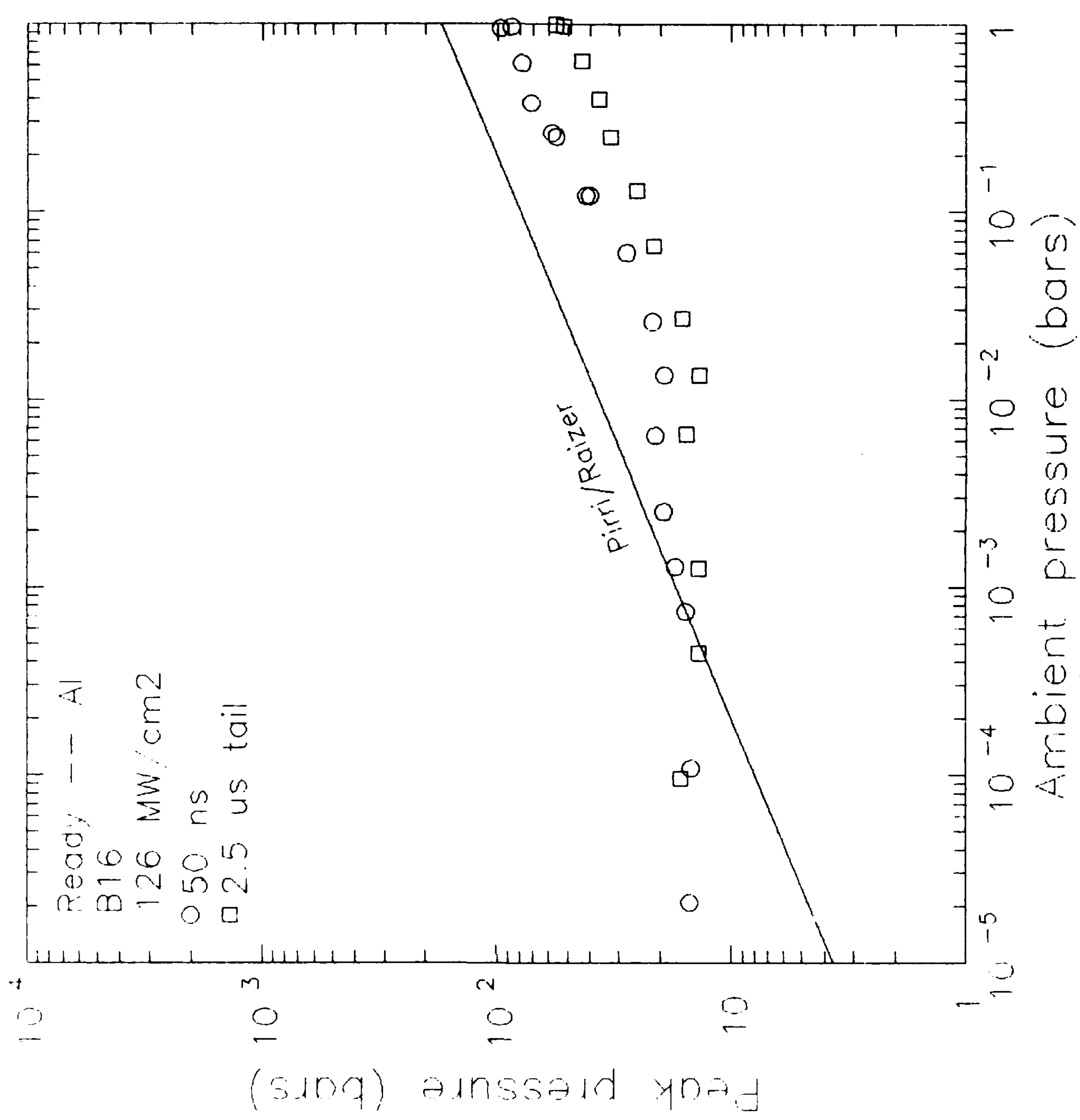
Measurement technique: rear-surface interferometry. "In addition measurements made as a function of target thickness indicate that the peak shock pressure is attenuated by approximately 20 percent in transmission through 0.6-mm inches (sic) of target material."

Figure caption: "Peak shock pressure as a function of ambient air pressure for an aluminum target irradiated at 1.26×10^8 W/cm^2."

Comments: The measured peak pressures, even with a 20% adjustment for attenuation in the target thickness, are well below the Raizer-Pirri line. This can be attributed to incomplete LSD formation with these short pulses. The "N_2 on" data lie well above the "N_2 off" values due to the more complete plasma formation, but remain below the Raizer-Pirri line due to the lower time-average laser intensity driving the LSD.

The dependence of peak pressure on ambient air pressure is, for pressures above 0.1 bar, quite close to the cube-root expected. At about 0.03 bars ambient pressure the peak pressure converges to a constant value, presumably corresponding to metal ablation instead of air-plasma formation. No abrupt transition is evident.

The experimental conditions here are essentially identical to those of Dufresne et al. (B1), yet the dependence of peak pressure on ambient observed here is very different.


Ready — Al
B16
126 MW/cm2
○ 50 ns
□ 2.5 us tail
Piri/Raizer
Peak pressure (bars)
Ambient pressure (bars)
10^{4}
10^{3}
10^{2}
10
1
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

Reference # : B1

Authors : D. Dufresne, Ph. Bournot, J.P. Caressa, G. Bosca, and J. David

Citation: "Pressure and impulse on an aluminum target from pulsed laser irradiation at reduced ambient pressure", Appl. Phys. Lett. 38, 234-236 (1981)

Institution: Institut de Mecanique des Fluides de Marseille, Marseille, France; C.E.A. Limeil-Service H.D.E., St. Georges, France

Experimental Conditions:

Laser: TEA CO_2
Wavelength: 10.6 μm
Pulse energy: to 200 J
Pulse duration: 50 ns spike; 2.5 μs N2 tail, depending on gas mix
Intensity range: 150 MW/cm2 (spike), 35 MW/cm2 (tail)
Atmosphere: air, 1 atm to vacuum (1.5 Torr)

Spot dimensions: 1.5 cm diameter

Target materials: aluminum

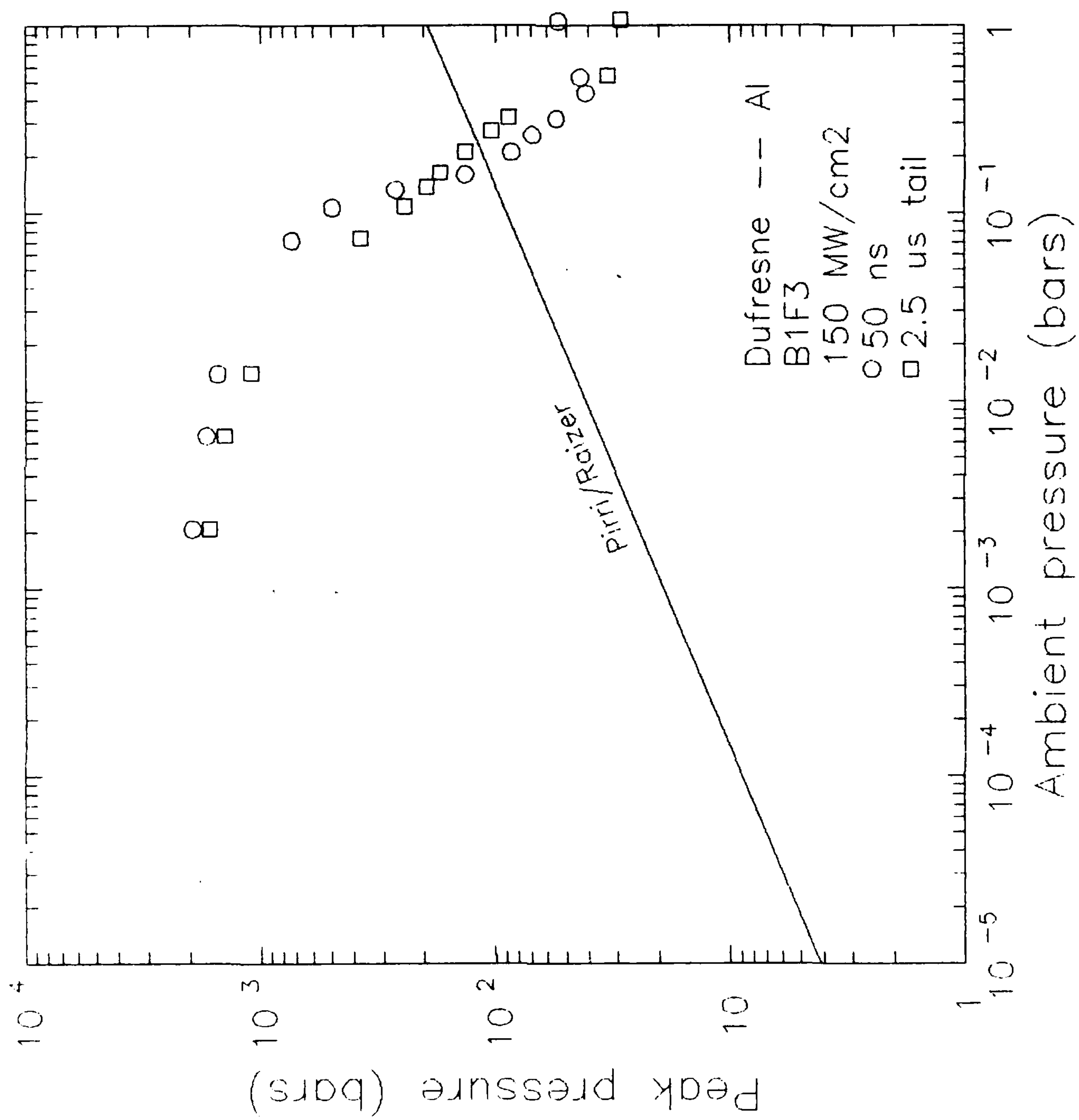
Target dimensions: 6 cm diameter, 0.1 cm thick

Measured quantities: pressure

Measurement technique: *carbon (Dynasen) piezoresistive* gauges, 1.27x0.635 mm

Figure caption: "Pressure on the target vs. [ambient pressure]"

Comments: The peak pressure is little affected by the presence or absence of the low-power pulse tail, indicating dominance of the high-power spike for this particular pulse shape. The transition from air-plasma behavior to vacuum behavior is gradual, rather than abrupt, over the range 10-200 Torr. The dependence on ambient pressure is wholly different from the prediction of the Pirri-Raizer theory.


Peak pressure (bars)
10^4
10^3
10^2
10
1
10^-5
10^-4
10^-3
10^-2
10^-1
1
Ambient pressure (bars)
Pirri/Raizer
Dufresne -- Al
B1F3
150 MW/cm2
o 50 ns
□ 2.5 us tail

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PRESSURE (STRESS) MEASUREMENTS IN VACUUM

#	1st author	yr	wavel	matls
B31	McMordie	1975	10.6 μm	Aluminum, DTD 5104 alloy
B17	Boiko	1977	10.6 μm	Lead
T2TB1V	Wilson	1986	0.35 μm	Aluminum, Chemglaze, and S-glass epoxy
T3	Holmes	1986	0.35 μm	Aluminum, epoxy layer on aluminum

PRESSURE (STRESS) DATA IN VACUUM

The following figures show the data available for peak-stress measurements in vacuum. The data are shown versus laser irradiance, the predominant independent variable for stress/pressure measurements in general. The range of irradiance is from 1×10^{6} W/cm^{2} to 1×10^{14} W/cm^{2}, covering the range of irradiances of interest for damage effects.

The list is very short. Two problems afflict these measurements, causing a paucity of data. The work related to laser fusion, upon which we have drawn heavily for this compilation, deals with laser beams focused to such small spots that conventional stress gauges cannot be used. So-called pressure data are obtained by making impulse measurements and assuming that deducing the pressure is possible by simply dividing the specific impulse by the pulse duration. This may well be valid for very short pulses but cannot be considered reliable for the full range of pulse durations important for laser effects work. We have incorporated those deduced-pressure data as impulse data. The Pirri model for pressure and impulse generation in vacuum [1], calculated for both these categories, will provide a convenient means of relating the two sets of data.

The second problem has to do with the opposite end of the irradiance spectrum. High-speed stress gauges work very well for hundred-kilobar stresses and up, even to the gigabar range. At the relatively modest stress levels developed in the range of principal interest to the effects community, 10^{8} - 10^{9} W/cm^{2}, the peak stress levels are under a kilobar, where fast measurements are quite difficult due to the low electrical signal levels. Measurements in the electrically noisy environment of laser interaction tests requires extremely careful attention to shielding, grounding, and circuit baseline balancing. Use of two gauges in a differential mode, as practiced by B.S. Holmes of SRI International, is one means of making such high-speed, low-level measurements. The problem of electrical interference from laser sources is in fact exceeded by electromagnetic interference generated by the plasma itself. Possibly related to "unipolar arcing", plasma-generated interference has prevented successful peak-stress measurements even in well-shielded, well-balanced detectors.

An additional complication in stress measurement is correction for acoustic effects within multilayered targets. Two techniques are commonly used for these measurements: Sandia-type quartz gauges bonded to thin sheets of the target material in question; and piezoresistive gauges, of carbon or ytterbium, embedded in multilayered sandwiches of target material, gauge (itself comprising three layers, two of insulator and one of piezoresistive conductor), and backing material. Acoustic reflections at each interface must be evaluated in order to work backwards from the stress observed at the gauge to the value that would prevail in the homogeneous material. Even if one has the computational tools for this task, uncertainty in the acoustic properties of target materials at kilobar stresses imposes some uncertainty in the calculated correction factors.

The major value of stress measurements, as opposed to impulse measurements, is in obtaining a one-dimensional line of data -- the stress versus time -- instead of single point measurement. We have not attempted to show stress-versus-time data here due to practical limitations.

Peak stress, and the attenuation of stress in passing through a target material, is a critical parameter in spall damage. This appears to be an area warranting further work.

Shown on each plot is the peak pressure predicted by the simple Pirri model [1], an extension of the Basov steady-state-ablation model [2]. Pirri's expression for the pressure at the target reduces to

$$P_s = 0.0425 \; [\; M^{7/2} \; c^2 \; \phi^7 \; / \; r_s \; l^2 \;]^{1/9} \; ,$$

where

P_s = peak pressure in d/cm²
M = atomic weight of the target material, amu
c = speed of light,
l = laser wavelength, in units consistent with c,
r_s = spot radius, cm,
ϕ = laser irradiance, W/cm².

The principal features of this expression are the $\phi^{7/9}$ dependence on irradiance and the $l^{-2/9}$ dependence on wavelength. The former appears to be confirmed by more detailed, numerical-code analysis [3], while a stronger dependence -- $l^{-2/3}$ -- is suggested for the wavelength. As will be evident from the data compiled here, the experimentally observed wavelength dependence is even weaker than the -2/9 power suggested by Pirri.

The Pirri model is by no means supposed to compete with sophisticated computer-code models, but is included as a general "reference" against which to compare the data. In two regimes it is not expected to be valid, even approximately: near ignition, where the energy lost to material vaporization is significant, and for large spots and short pulse durations, where a radial equilibrium flow of vaporized material cannot be set up. Nevertheless, as a cursory examination of the data plots will show, the model yields an excellent indication of the order of magnitude and general trends of the data over a remarkable range of laser irradiances and irradiance conditions.

[1] Anthony N. Pirri, "Theory for laser simulation of hypervelocity impact", Phys. Fluids 20, 221-228 (1977).

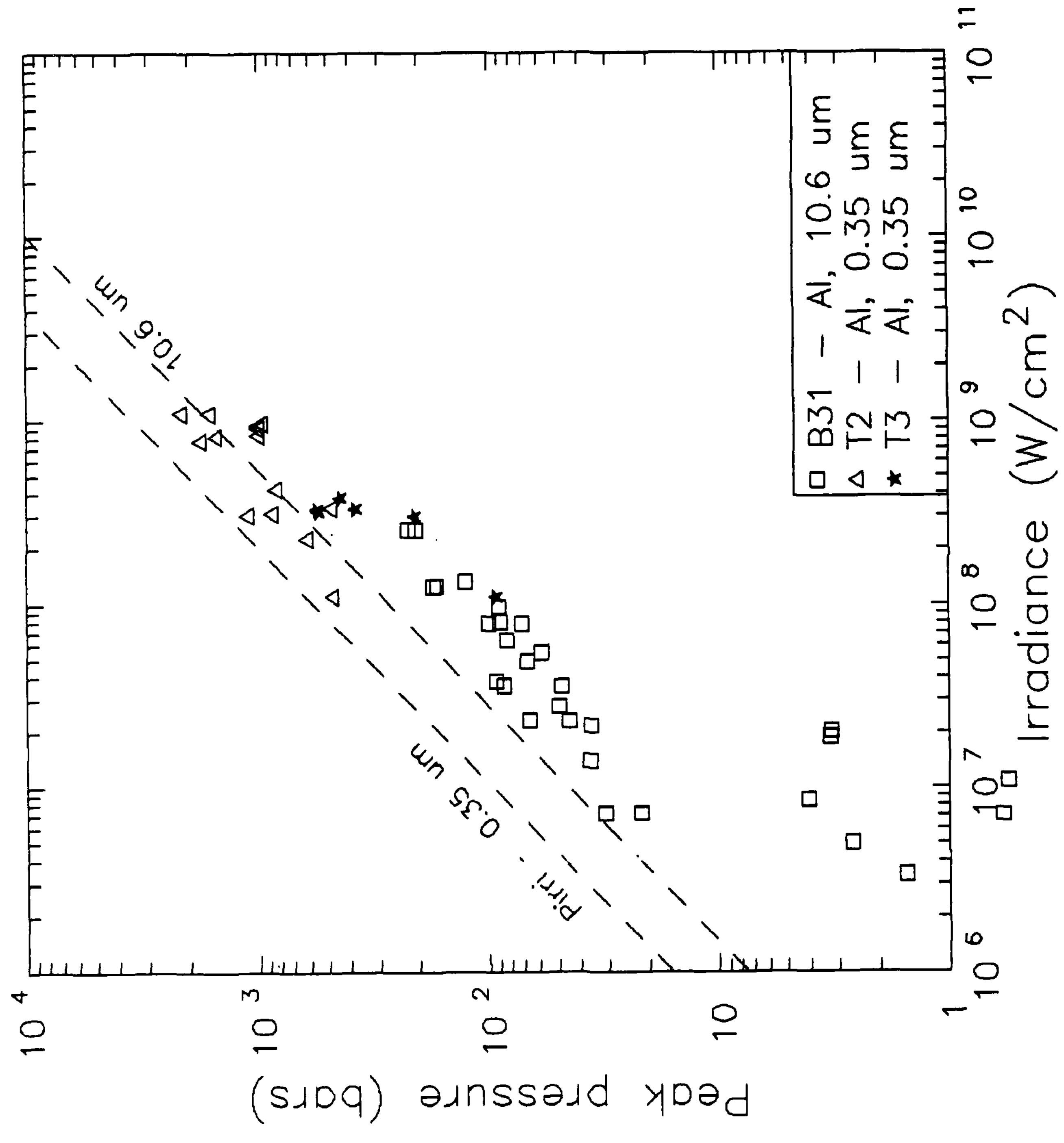
[2] N.G. Basov, V.A. Gribkov, O.N. Krokhin, and G.V. Sklizkov, "High temperature effects of intense laser emission focused on a solid target", Sov. Phys. JETP 27, 575-582 (1968).

[3] B. Meyer and G. Thiell, "Experimental scaling laws for ablation parameters in plane target-laser interaction with 1.06 μm and 0.35 μm laser wavelengths", Phys. Fluids 27, 302-311 (1984).

All aluminum pressure data in vacuum

The compilation of all peak-pressure data on aluminum shows very close to the 7/9 power dependence predicted by the Pirri model, and modest agreement with the predicted magnitudes, though in general the experimental data are a factor two to three lower than predicted. The wavelength dependence indicated by the data is vanishingly small. While the predicted dependence is weak -- a -2/9 power --the wavelength range here is so great that the difference should be evident.

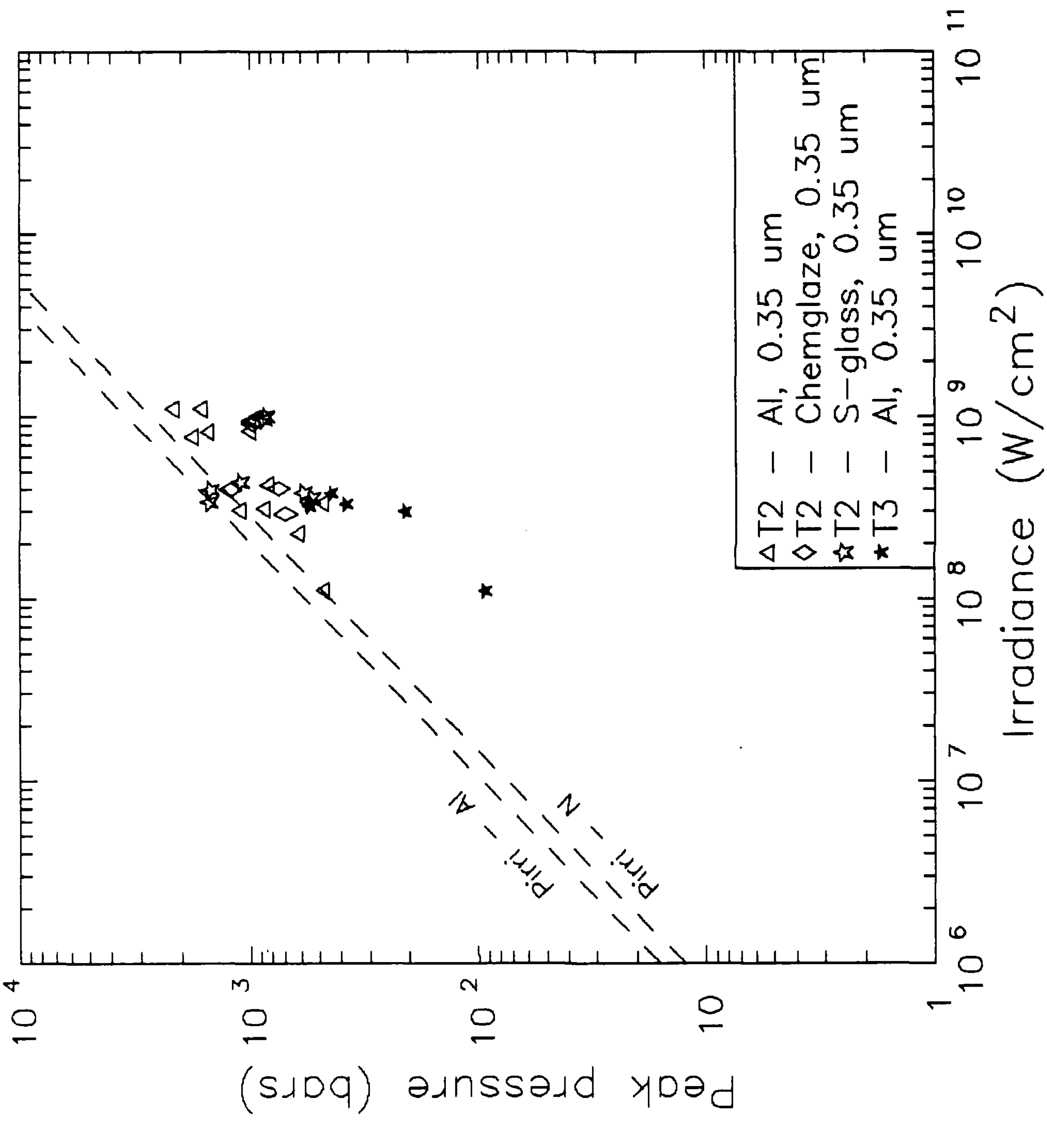
The model calculation assumed a spot diameter of 1 cm, while the experimental data ranged from 0.16 to 2 cm in diameter. The spot-diameter dependence is so weak -- the -1/9 power -- that its effect should be negligible.


Peak pressure (bars)
Irradiance (W/cm^2)
B31 – Al, 10.6 um
T2 – Al, 0.35 um
T3 – Al, 0.35 um
10.6 um
Pirri - 0.35 um
10^4
10^3
10^2
10
1
10^6
10^7
10^8
10^9
10^{10}
10^{11}

All UV-laser pressure data in vacuum

This collection of UV-laser pressure data shows the ability of the Pirri model to predict the pressure generation within a factor two or three, the data generally lying lower than the prediction. The largest discrepancies occur on aluminum data taken with the largest laser. Ignition delay might be a factor there.

The target-material dependence predicted by the model is not evident in the data, though the difference is small enough that it would be difficult to discern, given the scatter in the data.



Peak pressure (bars)
Irradiance (W/cm^2)
10^4
10^3
10^2
10
1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Pirri Al
Pirri N
△T2 — Al, 0.35 um
◇T2 — Chemglaze, 0.35 um
☆T2 — S-glass, 0.35 um
★T3 — Al, 0.35 um

Reference # : B31

Authors : J.A. McMordie and P.D. Roberts

Citation: "The interaction of pulsed CO_2 laser radiation with aluminium", J. Phys. D. 8, 768-781 (1975)

Institution: Atomic Weapons Research Establishment, Aldermaston, Reading, UK

Experimental Conditions:
- Laser: TEA CO_2
  - Wavelength: 10.6 μm
  - Pulse energy: (a) 100 J, (b) 60 J, (c) 15 J
  - Pulse duration: (a) 3.1 μs, (b) 2.0 μs, (c) 175 ns
- Intensity range: 3 - 300 MW/cm^2
- Atmosphere: vacuum, <0.1 Torr (1×10^{-4} bars)

Spot dimensions: Variable, 0.4 - 2 cm diameter

Target materials: Aluminum, DTD 5104 alloy, mechanically polished (emery paper followed by steel wool)

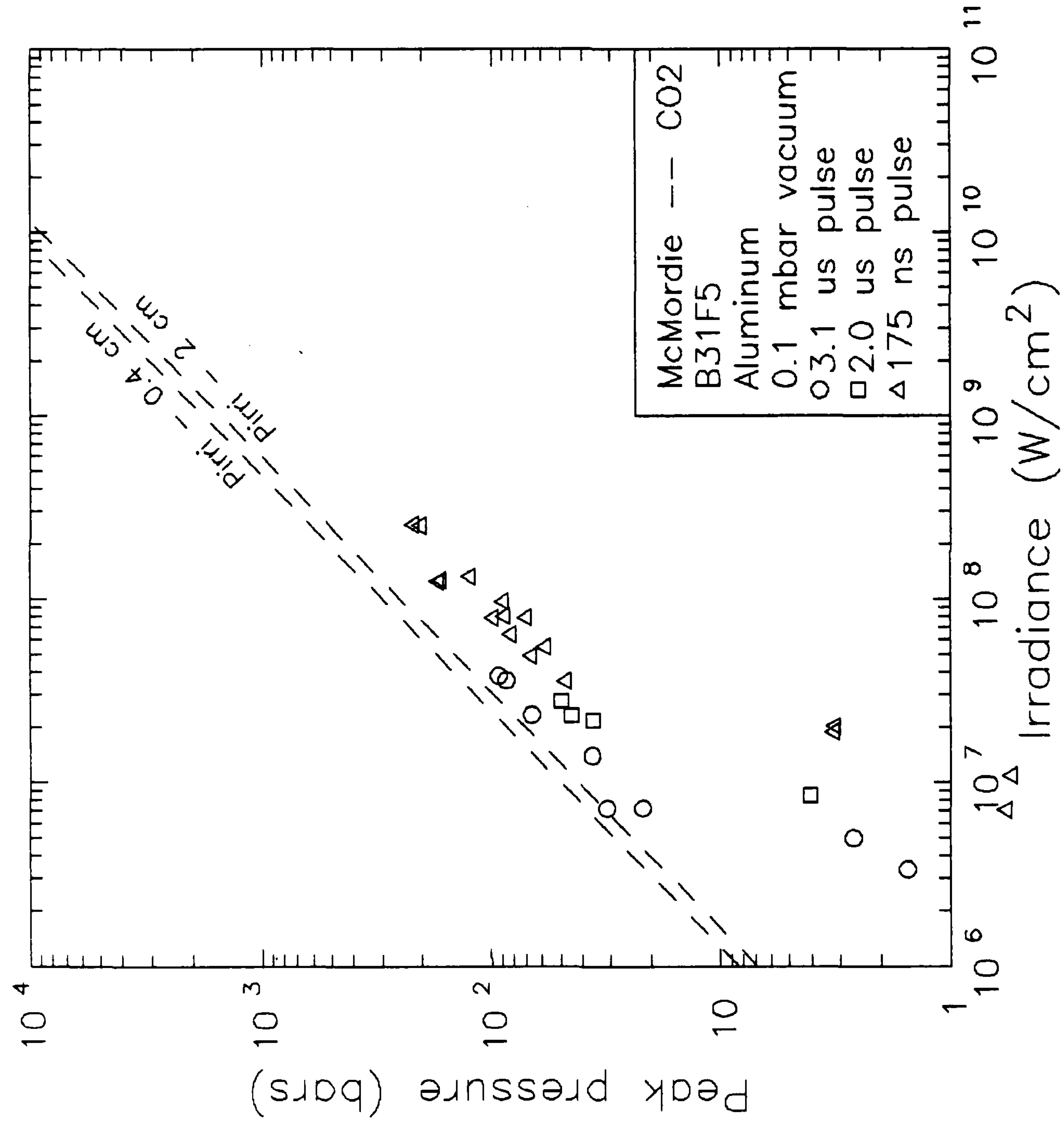
Target dimensions: 5.4 cm diam by 0.66 mm thick

Measured quantities: pressure

Measurement technique: quartz piezoelectric (Sandia type), 0.18 cm active diameter, 0.5 cm length

Figure caption: "Peak pressure against peak power, incident on 0.66 mm thick DTD5104 aluminium alloy."

Comments: The peak pressure, for laser irradiances above 10 MW/cm^2, is in very good agreement with the Pirri model, including the predicted 7/9 irradiance dependence.



McMordie — CO2
B31F5
Aluminum
0.1 mbar vacuum
○ 3.1 us pulse
□ 2.0 us pulse
△ 175 ns pulse
0.4 cm
2 cm
Pirri
Pirri
Peak pressure (bars)
Irradiance (W/cm²)
10⁴
10³
10²
10
1
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹

Reference # : B17

Authors : V.A. Boiko, V.A. Danilychev, B.N. Duvanov, V.D. Zvorykin, I.V. Kholin, and A. Yu. Chugunov

Citation: "Measurement of gasdynamic pressure on a target subjected to CO_2 laser radiation", Sov. J. Quantum Electron. 7, 465-468 (1977)

Institution: P.N. Lebedev Physics Institute, Moscow

Experimental Conditions:
- Laser: e-beam CO_2
  - Wavelength: 10.6 μm
  - Pulse energy: 100 J
  - Pulse duration: 120 ns fwhm, 450 ns total.
- Intensity range: 10 - 1000 MW/cm^2
- Atmosphere: 0.07 Torr (9×10^{-5} bar)

Spot dimensions: 1.5 and 2.8 cm^2

Target materials: Lead

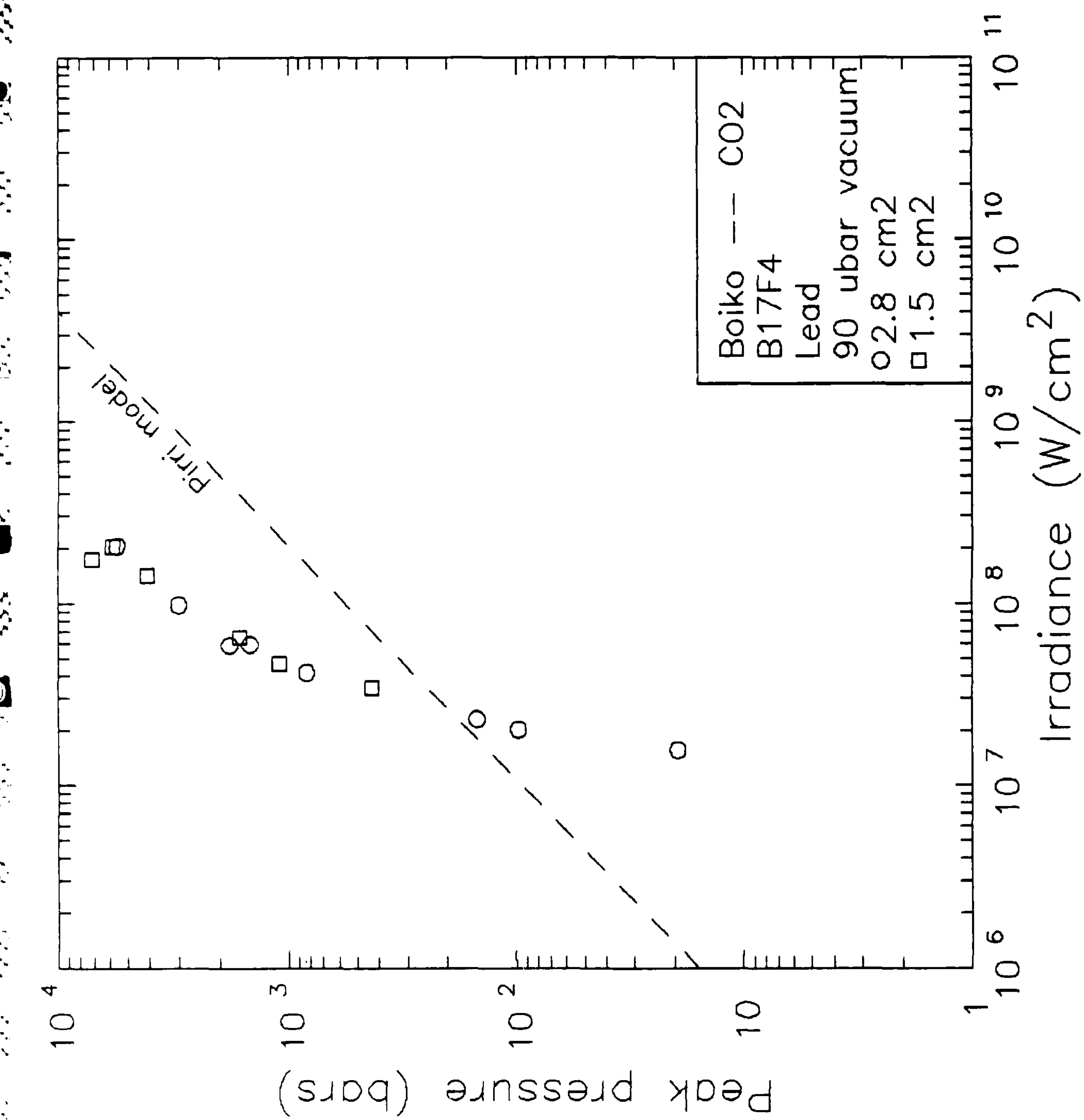
Target dimensions: 1 cm diameter foils, thickness 0.7 mm (Pb)

Measured quantities: pressure

Measurement technique: quartz piezoelectric (Sandia type), 0.4 cm active diameter, 0.1 cm length (175 ns writing time); in "acoustic contact" with target specimens

Figure caption: "Dependences of the amplitude of the pressure on a lead target in vacuum on the maximum laser power density (energy density) obtained for [area] 1.5 and 2.8 cm^2."

Comments: This ablation-pressure coupling on lead increases as about the 3/2 power of the laser irradiance. The data disagree substantially with the Pirri ablation model.



Boiko --- CO2
B17F4
Lead
90 ubar vacuum
o 2.8 cm2
□ 1.5 cm2
Pirri model
Irradiance (W/cm^2)
Peak pressure (bars)
10 6
10 7
10 8
10 9
10 10
10 11
1
10
10 2
10 3
10 4

Reference # : T2TB1V

Authors : R.S. Wilson

Citation: "Measurements of material response to excimer laser irradiation", S-Cubed report SSS-R-86-7629 (30 Jan 1986)

Institution: S-Cubed Inc., La Jolla CA

Experimental Conditions:

Laser: Maxwell Laboratories 2-meter excimer (XeF)

Wavelength: 0.35 μm

Pulse energy: 75 J

Pulse duration: 1.8 μs

Intensity range: 100 - 1000 MW/cm^2

Atmosphere: vacuum, 0.05 - 5 Torr (70 μbar - 7 mbar)

Spot dimensions: (a) 0.27x0.135 cm, (b) 0.41x0.205 cm, (c) 0.49x0.245 cm

Target materials: Aluminum, Chemglaze, and S-glass epoxy

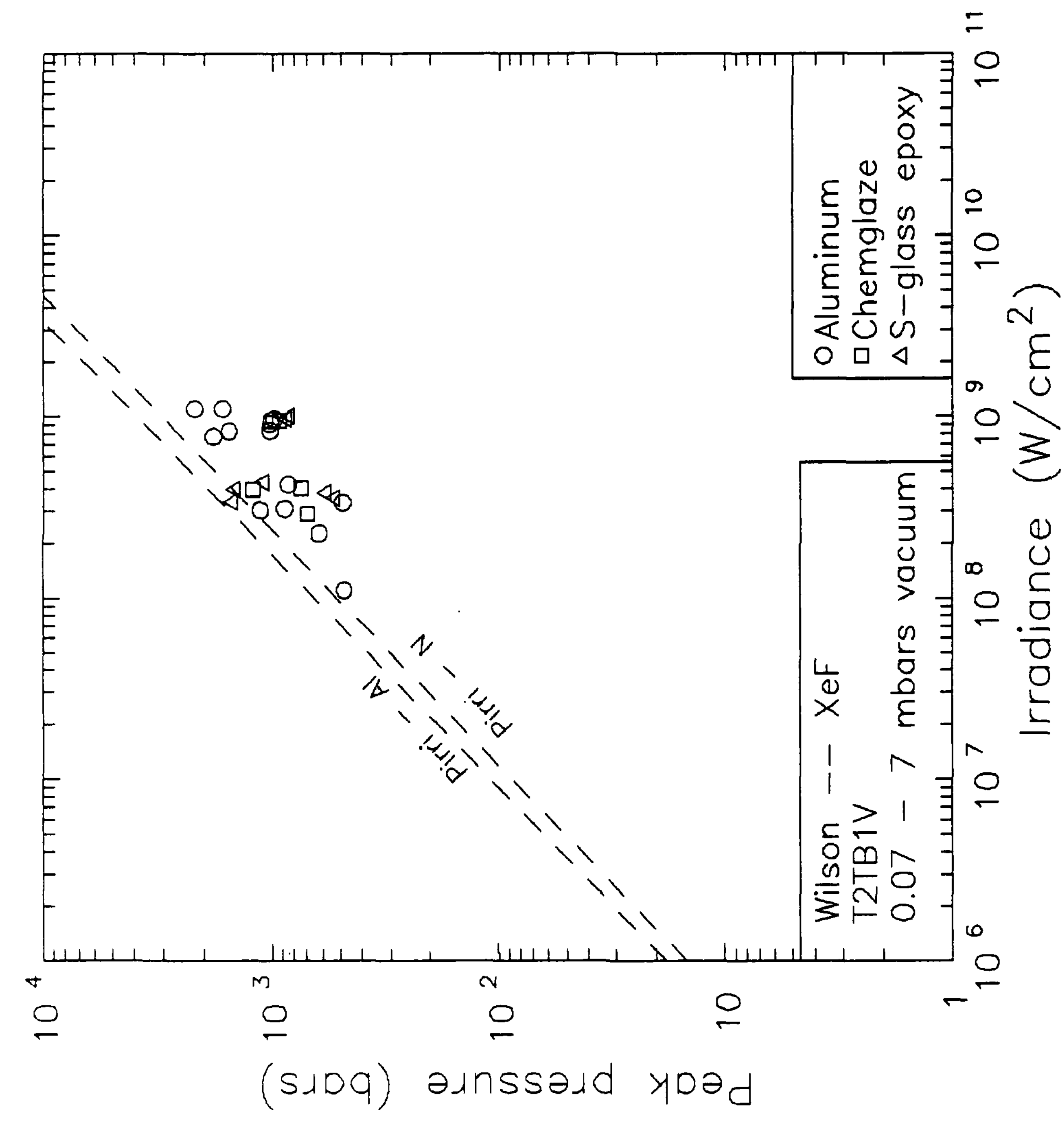
Target dimensions: 0.95 cm diam

Measured quantities: pressure and total impulse

Measurement technique: (a) pressure: ytterbium piezoresistive gauge, (b) impulse: optical velocity transducer behind block suspended on loose membrane

Table caption: "Summary of test results."

Comments: These peak-stress data are in remarkably good agreement with the simple Pirri model.



Peak pressure (bars)
Irradiance (W/cm^2)
Wilson -- XeF
T2TB1V
0.07 - 7 mbars vacuum
○ Aluminum
□ Chemglaze
△ S-glass epoxy
Pirri
N
Pirri
Al

Reference # : T3

Authors : Bayard S. Holmes

Citation: "Assessment of the vulnerability and lethality of aerospace systems, volume II: laser coupling measurements", Technical Report DNA-TR-85-000, May 1986

Institution: SRI International, Menlo Park CA

Experimental Conditions:

Laser: Transverse e-beam XeF (Avco "Scale-up")

Wavelength: 0.35 μm

Pulse energy: 240 J

Pulse duration: 1.5 μs

Intensity range: 100 - 300 MW/cm^2

Atmosphere: vacuum, 3 - 10 Torr (4 - 13 mbar)

Spot dimensions: 0.80 and 1.25 cm diameter

Target materials: Aluminum, epoxy layer on aluminum

Target dimensions: 0.95 cm diam

Measured quantities: pressure and total impulse

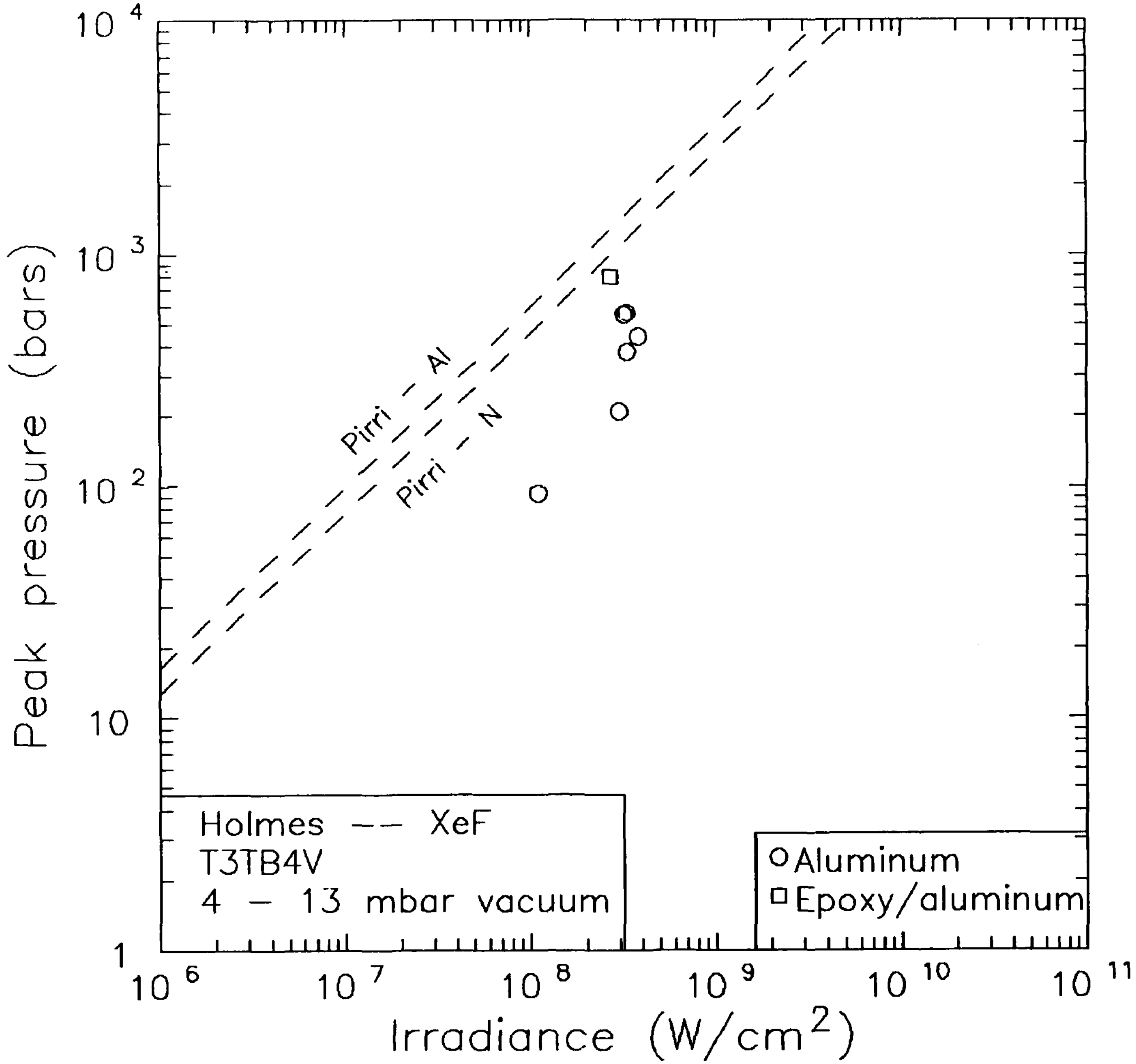
Measurement technique: ytterbium piezoresistive gauge

Table caption: "Summary of data from the in-vacuum experiments."

Comments: The peak stress increases here as about the 4/3 power of laser irradiance. The pressure-time traces are similar in shape to the shape of the laser pulse, a fairly smooth ramp terminated abruptly at the peak value.

The epoxy on aluminum was a simple attempt to compare the pressure-time on epoxy versus that on aluminum. The stress wave shape was very different for this single specimen, the peak occurring very early in time, not at all similar to the ramp-shaped waves observed on aluminum.

The Pirri model predicts a negligible dependence on spot diameter and a modest variation with atomic weight. The observed change in peak pressure with the epoxy layer is in the opposite direction to that predicted. The values observed on aluminum are significantly lower than predicted.



Peak pressure (bars)
Irradiance (W/cm^2)
10^4
10^3
10^2
10
1
10^6
10^7
10^8
10^9
10^10
10^11
Pirri – Al
Pirri – N
Holmes –– XeF
T3TB4V
4 – 13 mbar vacuum
Aluminum
Epoxy/aluminum

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IMPULSE MEASUREMENTS IN AIR

#	1st au	yr	wavel	matls
B22	Pirri	1972	10.6	Aluminum, carbon, and tungsten
B35	Hettche	1973	10.6	Aluminum
M33	Metz	1975	10.6	Aluminum, stainless steel, alumina, magnesium oxide, graphite, fiberglass, calcium oxide, lucite, titanium, Lucalox
B15	Barchukov	1976	10.6	Magnesium, glass, anodized aluminum, or copper-coated glass
T4	French	1983	10.6	aluminum, carbon
B27	Searles	--	2.7	Aluminum
B28	Bohn	1985	1.315	Aluminum
B20	Batanov	1973	1.06	Aluminum, iron, lead, Wood's alloy, bismuth
B4	Rudder	undated	1.06	Titanium 6Al-4V
B39	Rudder	1973	1.06	Titanium 6Al-4V, aluminum, graphite
B32	Metz	1973	1.06	Aluminum, carbon
B23	Kozlova	1975	1.06	Aluminum
B33	Hettche	1976	1.06	Aluminum, titanium 6Al-4V
T5	French	1983	1.06	aluminum, carbon
T3	Holmes	1986	1.06	aluminum, carbon
B12	Kuriki	1977	0.69	Gold, nickel, molybdenum
B38	Woodroffe	1980	0.25, 0.35	Aluminum

IMPULSE DATA IN AIR

The following figures show the data available for impulse delivery in air. Impulse generation by a laser-driven air plasma is a rather complex phenomenon, the quantity of impulse delivered being a function not only of the specific laser parameters -- pulse duration and irradiance -- but of the spot dimensions, due to pressure relaxation effects, and of the target dimensions, due to blast-wave expansion effects. Simple display and intercomparison of data sets is practically impossible.

In most cases, most of the impulse delivered is generated not during the laser pulse but by the blast wave long after the pulse. A zeroth-order model for impulse delivery is to model the laser pulse as an instantaneous delivery of energy to the air immediately above the target surface, then compute the pressure-time due to the expansion and decay of that bubble of heated air, ignoring the dynamics during the laser pulse. The situation is not very different from a rapid chemical explosion releasing the same amount of energy.

The most significant parameter of the interaction thus appears to be simply the total energy delivered by the laser pulse. The laser irradiance, while governing the peak pressure generated, is not very important in the determination of the impulse delivery.

At that level of examination, the coupling ought to be independent of all the laser parameters. In fact, the dimensionality of the laser interaction does affect the impulse delivery. Long pulses and small laser spots, highly two-dimensional interactions, lead to cylindrical blast-wave decay. Short pulses and large laser spots lead instead to axial decay. The blast-wave decay scaling laws differ for the modes of pressure relaxation, leading in turn to different impulse deliveries and coupling coefficients.

The model for air-plasma impulse delivery by G.A. Simons [1] evaluates impulse delivery by careful connection of the various dimensionality modes of blast wave decay, conserving energy at the expense of accuracy in the details of the pressure versus time at the target surface. Simons defines eight distinct regimes, each corresponding to a certain permutation of inequalities involving the laser pulse duration, the laser spot diameter, and the laser target dimensions. The result, eight different analytic expressions for the impulse delivery, is sufficiently complex that it will not be repeated here, but is amenable to solution by a short computer program. This has been used to generate theory lines for each of the data sets in the following pages.

In keeping with the logic above, the impulse data are plotted versus laser pulse energy. This is not entirely satisfactory since it fails to distinguish between short, high-power pulses and long, low-power pulses, interactions of very different dimensionality. Every other possible selection for the principal independent variable suffers from similar shortcomings. Plots versus laser irradiance, for example, would put high-energy, large-spot experiments, with low-dimensionality interaction, together with low-energy, small-spot work, with very high dimensionality.

Some experiments are not suitable for this manner of display. In the ideal

air-impulse experiment the laser pulse duration and the spot dimensions are held constant, thus fixing (approximately) the dimensionality. This is not the easiest way to do an experiment, and many workers have chosen to keep the pulse energy fixed and vary the spot dimensions. This causes the dimensionality to vary drastically across a set of data. Since the energy-variable manner of data display would put the results of these experiments at a single abscissa location, an unsatisfactory result, those particular works have been shown as functions of laser fluence (energy per unit area).

The meaning of I/E must be made clear. If radial expansion of the blast wave were not a factor, and the impulse were confined to the laser spot, then there would be no difference between (1) the ratio of impulse intensity, in d-s/cm2, to laser fluence, in J/cm2, and (2) the ratio of total impulse, in dyne-seconds, to total laser pulse energy, in joules. Since the units of these ratios are identical, there is frequent confusion between these two ratios. Because blast wave expansion delivers impulse well outside the laser spot, these two ratios are definitely not identical for the air interaction (they may be identical in vacuum, though even this is not always true).

The data plots here show the ratio of total impulse delivered to total pulse energy applied. Clearly the target area is a significant factor, short of the limiting case of a target so large that the blast wave decays to zero overpressure before reaching the target edge. The importance of the target dimensions has seldom been realized by experimenters, who tend to assume either that impulse delivery outside the laser spot is negligible or that their targets are larger than the radially expanding blast wave.

The data have been separated by laser wavelength, from CO_2 (10.6 μm) to KrF (0.25 μm). No data for wavelengths outside this range have been found.

[1] Girard A. Simons, "Momentum transfer to a surface when irradiated by a high-power laser", AIAA Journal 22, 1275-1280 (1984).

Reference # : B22

Authors : A.N. Pirri, R. Schlier, and D. Northam

Citation: "Momentum transfer and plasma formation above a surface with a high-power CO_2 laser", Appl. Phys. Lett. 21, 79-81 (1972)

Institution: Avco Everett Research Laboratory, Everett MA

Experimental Conditions:

- Laser: electron-beam-pumped CO_2
  - Wavelength: 10.6 μm
  - Pulse energy: 300 J
  - Pulse duration: 25 μs
- Intensity range: 4 - 100 MW/cm^2
- Atmosphere: 1 atm air

Spot dimensions: 0.16 and 0.87 cm diam

Target materials: aluminum, carbon, and tungsten (not distinguished in data publication)

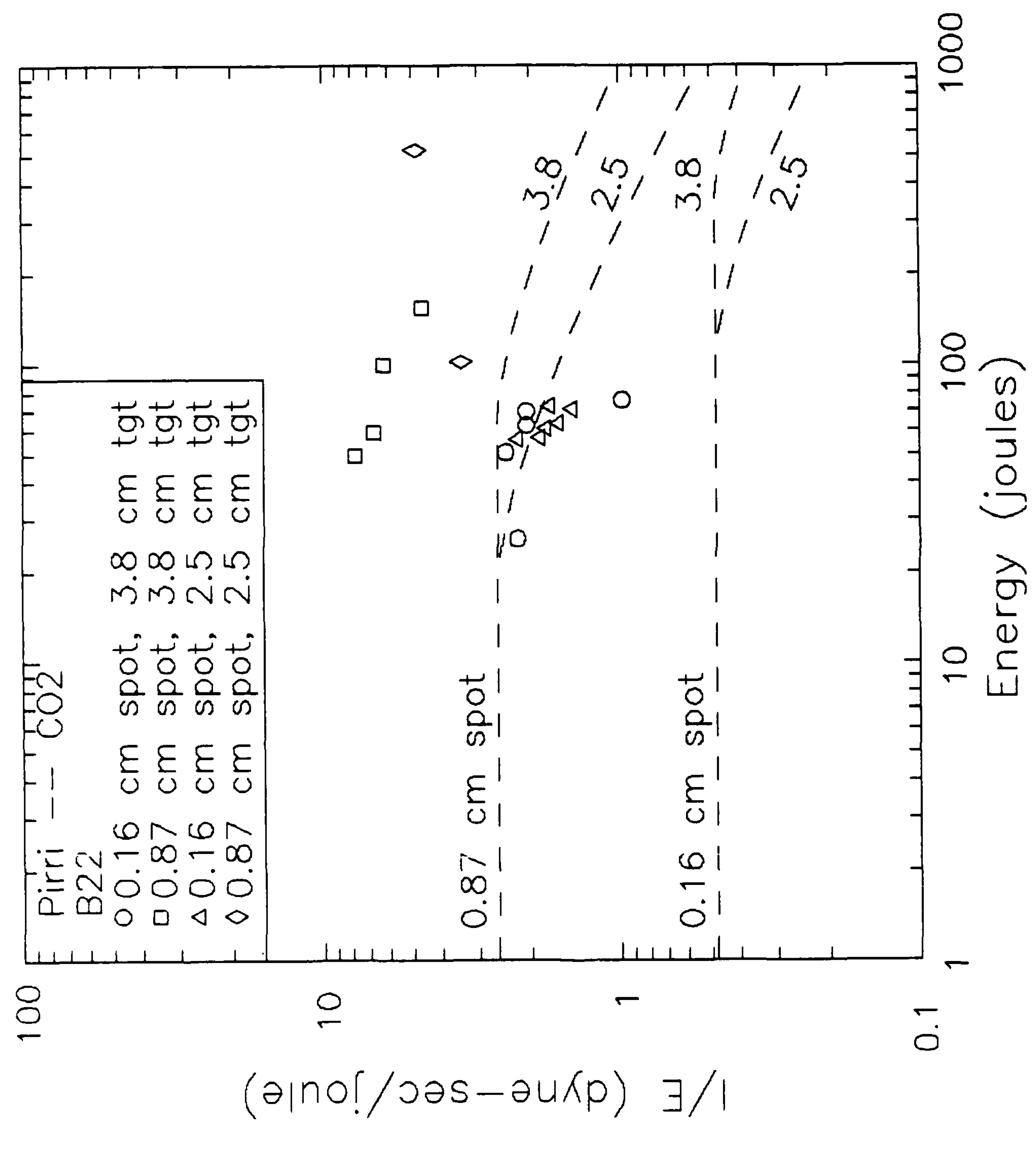
Target dimensions: 2.5 and 3.8 cm diam

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum.

Figure caption: "Data for momentum transfer versus energy per spot area."

Comments: These are among the earliest laser-delivered impulse data. As for other laser tests with long pulses and small spots -- highly two-dimensional interactions -- the Simons model does not do well.


Pirri --- CO2
B22
○ 0.16 cm spot, 3.8 cm tgt
□ 0.87 cm spot, 3.8 cm tgt
△ 0.16 cm spot, 2.5 cm tgt
◇ 0.87 cm spot, 2.5 cm tgt
0.87 cm spot
0.16 cm spot
3.8
2.5
3.8
2.5
I/E (dyne-sec/joule)
100
10
1
0.1
1
10
100
1000
Energy (joules)

Reference # : B35

Authors : L.R. Hettche, J.T. Schriempf, and R.L. Stegman

Citation: "Impulse reaction resulting from the in-air irradiation of aluminum by a pulsed CO_2 laser", J. Appl. Phys. 44, 4079-4085 (1973)

Institution: Naval Research Laboratory, Washington DC

Experimental Conditions:
Laser: electron-beam-pumped CO_2
Wavelength: 10.6 μm
Pulse energy: 100-700 J
Pulse duration: 15-50 μs
Intensity range: 10 - 100 MW/cm^2
Atmosphere: 1 atm air

Spot dimensions: 47% of energy within 0.1 cm^2, 43% in four symmetrical lobes (about 0.4 cm^2)

Target materials: aluminum, commercially pure

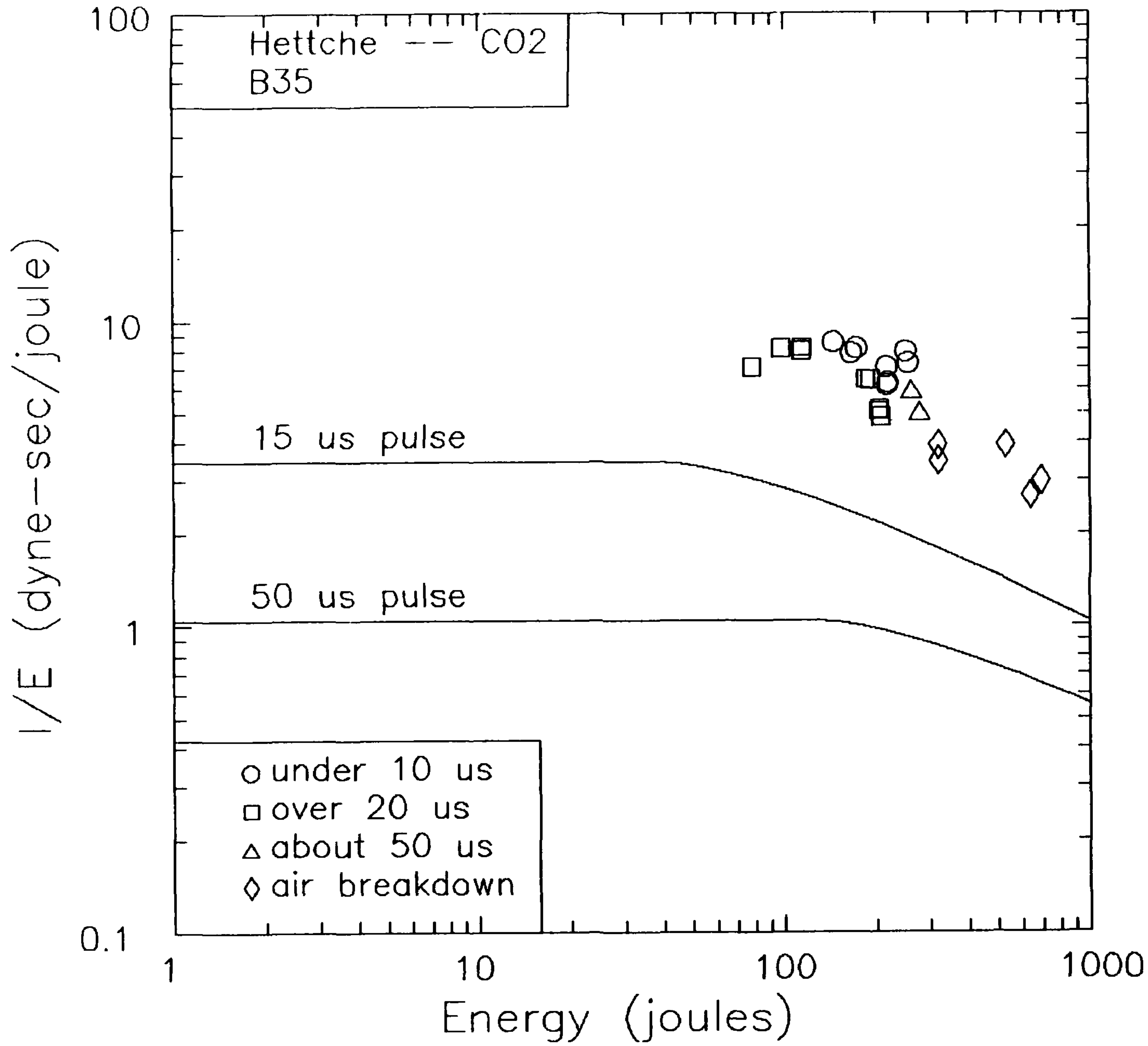
Target dimensions: 3.5 cm diameter, 0.05 cm thick

Measured quantities: total impulse

Measurement technique: ballistic pendulum, inclined for higher sensitivity

Figure caption: "Impulse vs beam energy defines a coupling coefficient (I/E) of between 5 and 7.8 dyn sec/J with no dependence on pulse length. Note the marked reduction in impulse when breakdown occurs along the beam path."

Comments: These impulse data lie well above the Simons model predicted values, for reasons unknown. The very poor spatial profile might be a factor.


Hettche -- CO2
B35
15 us pulse
50 us pulse
under 10 us
over 20 us
about 50 us
air breakdown
100
10
1
0.1
I/E (dyne-sec/joule)
1
10
100
1000
Energy (joules)

Reference # : M33 (1)

Authors : S.A. Metz, L.R. Hettche, R.L. Stegman, and J.T. Schriempf

Citation: "Effect of beam intensity on target response to high-intensity pulsed CO_2 laser radiation", J. Appl. Phys. 46, 1634-1642 (1975)

Institution: Naval Research Lab, Washington DC

Experimental Conditions:

Laser: shock-tube-driven gasdynamic CO_2

Wavelength: 10.6 μm

Pulse energy: 2.4 kJ

Pulse duration: 4-5 ms

Intensity range: 0.1 - 10 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: Not given

Target materials: Aluminum, stainless steel, alumina, magnesium oxide, graphite, fiberglass, calcium oxide

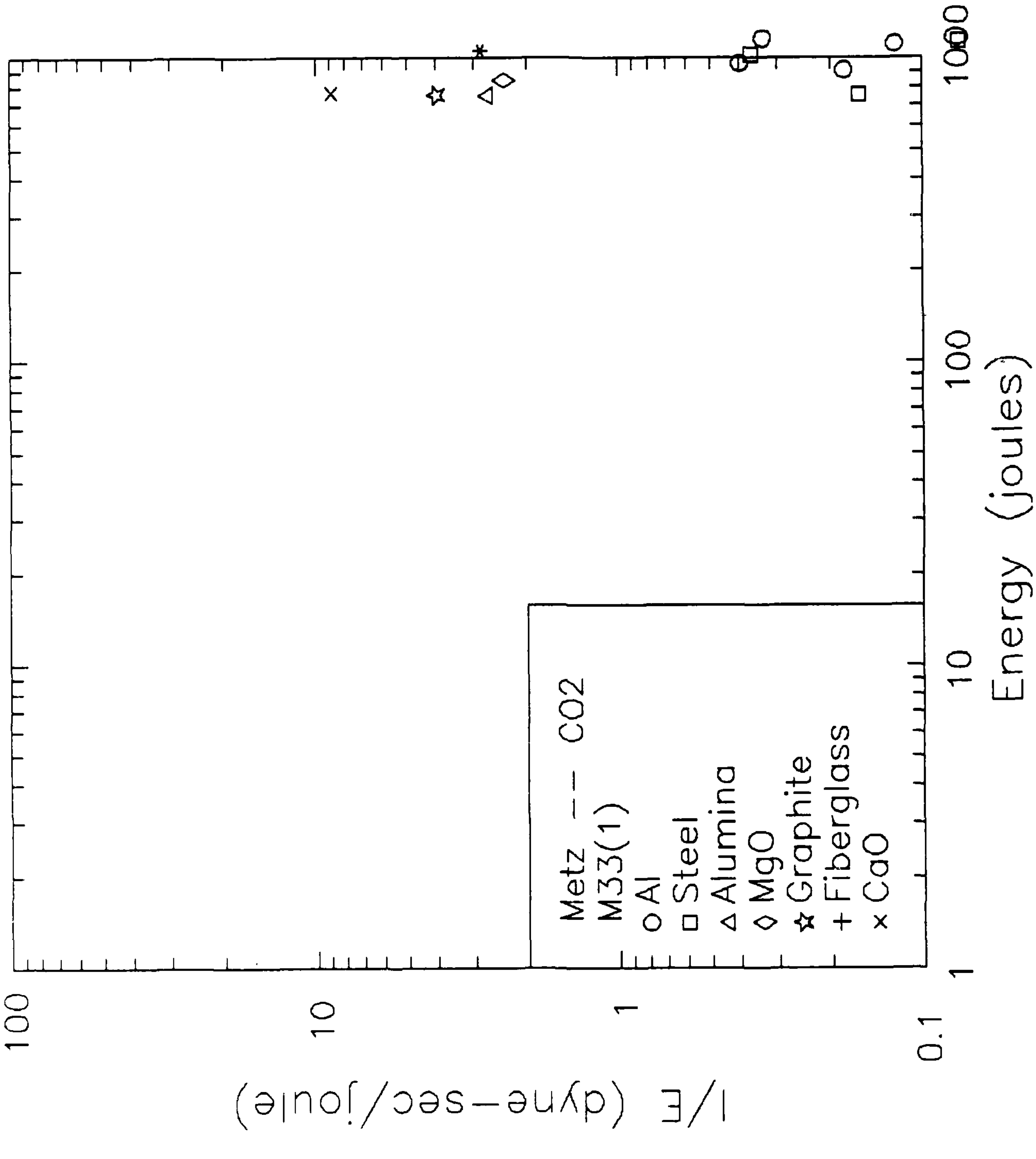
Target dimensions: 1 cm^2

Measured quantities: Total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Impulse delivered to targets of various materials by 5×10^{-3}-sec 10.6-μm-wavelength laser pulse as function of beam energy."

Comments: The impulse here is generated by target ablation, not by air plasmas, thus leading to substantial differences between nonmetals, vaporizing relatively easily, and metals, so reflective that vaporization is small.


Metz -- CO2
M33(1)
Al
Steel
Alumina
MgO
Graphite
Fiberglass
CaO
Energy (joules)
I/E (dyne-sec/joule)
1
10
100
1000
0.1
1
10
100

Reference # : M33 (2)

Authors : S.A. Metz, L.R. Hettche, R.L. Stegman, and J.T. Schriempf

Citation: "Effect of beam intensity on target response to high-intensity pulsed CO_2 laser radiation", J. Appl. Phys. 46, 1634-1642 (1975)

Institution: Naval Research Lab, Washington DC

Experimental Conditions:
Laser: shock-tube-driven gasdynamic CO_2
Wavelength: 10.6 μm
Pulse energy: 300 J
Pulse duration: 300 μs
Intensity range: 0.1 - 10 MW/cm^2
Atmosphere: 1 atm air

Spot dimensions: Not given

Target materials: Aluminum, alumina, magnesium oxide, lucite, graphite, titanium

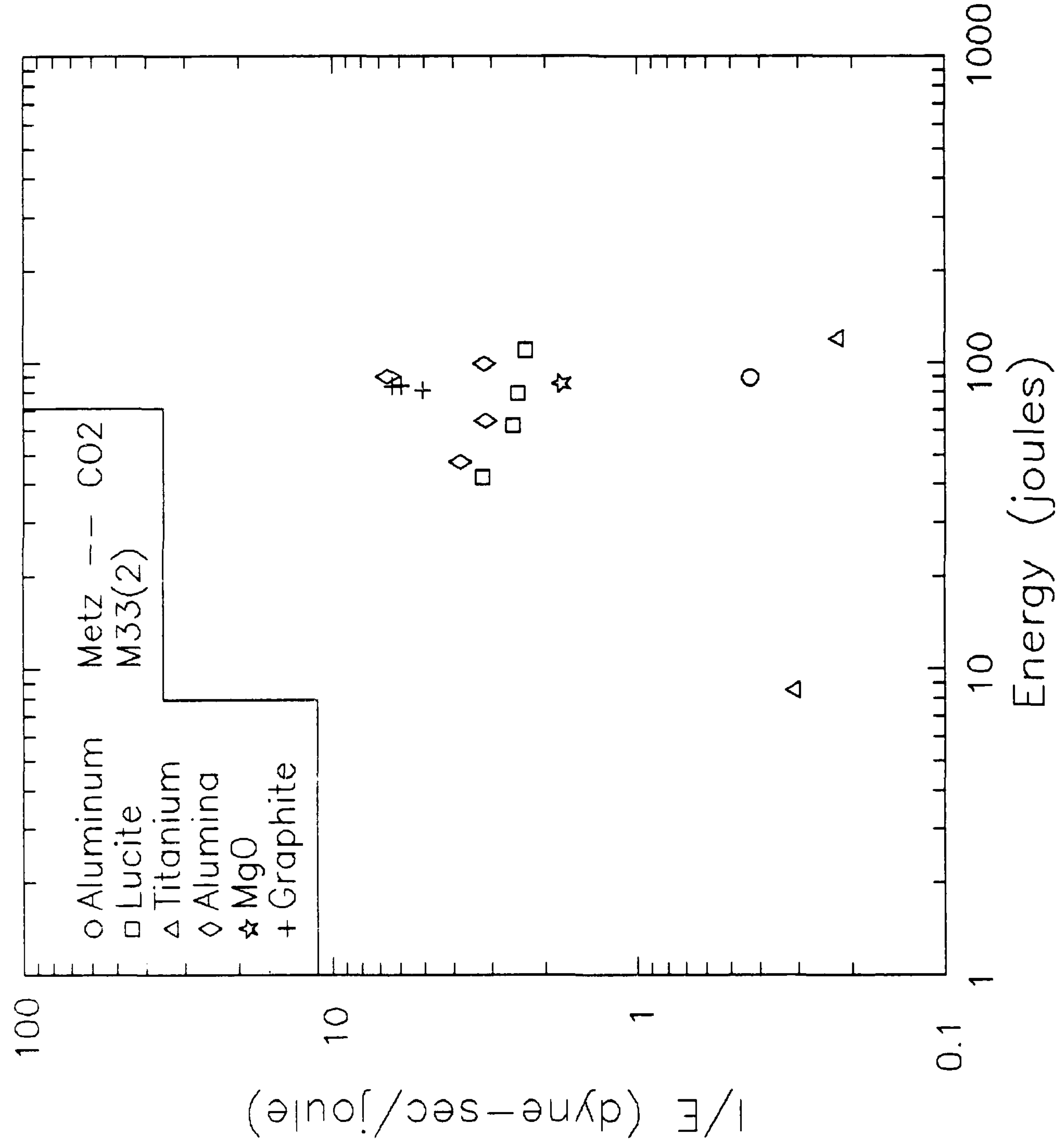
Target dimensions: 1 cm^2

Measured quantities: Total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Impulse delivered to targets of various materials by $3x10^{-4}$-sec 10.6-μm-wavelength laser pulse as function of beam energy."

Comments: The impulse here is generated by target ablation, not by air plasmas, thus leading to substantial differences between nonmetals, vaporizing relatively easily, and metals, so reflective that vaporization is small.



Metz -- CO2
M33(2)
○ Aluminum
□ Lucite
△ Titanium
◇ Alumina
☆ MgO
+ Graphite
I/E (dyne-sec/joule)
100
10
1
0.1
Energy (joules)
1
10
100
1000

Reference # : M33 (3)

Authors : S.A. Metz, L.R. Hettche, R.L. Stegman, and J.T. Schriempf

Citation: "Effect of beam intensity on target response to high-intensity pulsed CO_2 laser radiation", J. Appl. Phys. 46, 1634-1642 (1975)

Institution: Naval Research Lab, Washington DC

Experimental Conditions:

Laser: electron-beam-pumped CO_2 (MIT - Lincoln Laboratories)

Wavelength: 10.6 μm

Pulse energy: 500 J

Pulse duration: 20 μs

Intensity range: 50 - 5000 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: 0.04 cm^2 ("nominal")

Target materials: Aluminum, lucite, graphite, Lucalox ("a fine-grained polycrystalline Al_2O_2 [sic]")

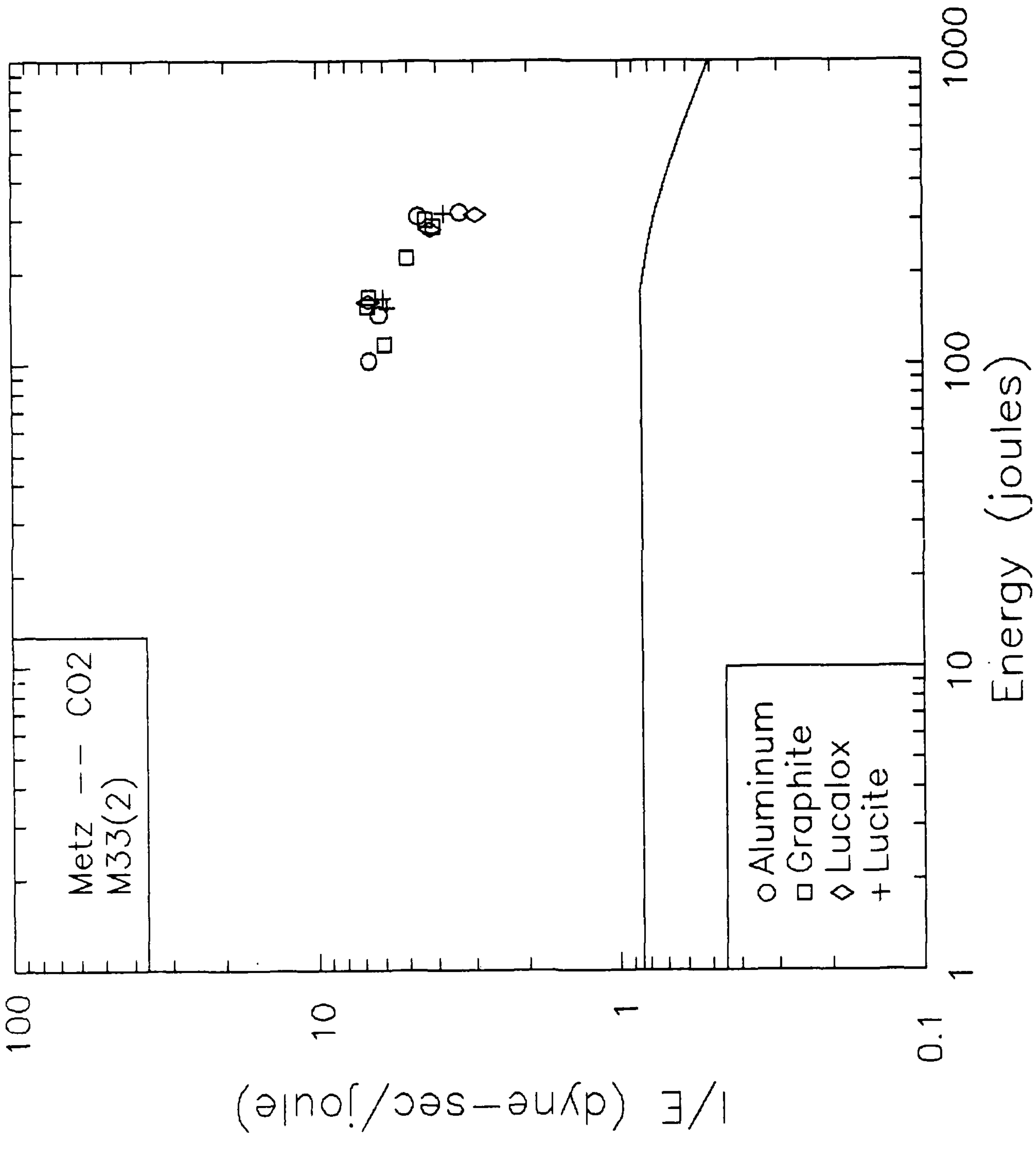
Target dimensions: 0.78, 5, 10, and 19.6 cm^2

Measured quantities: Total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Impulse delivered to targets of various materials by $2x10^{-5}$-sec 10.6-μm-wavelength laser pulse as function of beam energy."

Comments: The data here lie well above the values predicted by the Simons model. This is a regime of very small laser spot diameter relative to the pulse duration.


Metz -- CO2
M33(2)
Aluminum
Graphite
Lucalox
Lucite
Energy (joules)
I/E (dyne-sec/joule)
1
10
100
1000
0.1
1
10
100

Reference # : M33 (4)

Authors : S.A. Metz, L.R. Hettche, R.L. Stegman, and J.T. Schriempf

Citation: "Effect of beam intensity on target response to high-intensity pulsed CO_2 laser radiation", J. Appl. Phys. 46, 1634-1642 (1975)

Institution: Naval Research Lab, Washington DC

Experimental Conditions:

Laser: electron-beam-pumped CO_2 (MIT - Lincoln Laboratories)

Wavelength: 10.6 μm

Pulse energy: 500 J

Pulse duration: 20 μs

Intensity range: 50 - 5000 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: 0.04 cm^2 ("nominal")

Target materials: Aluminum

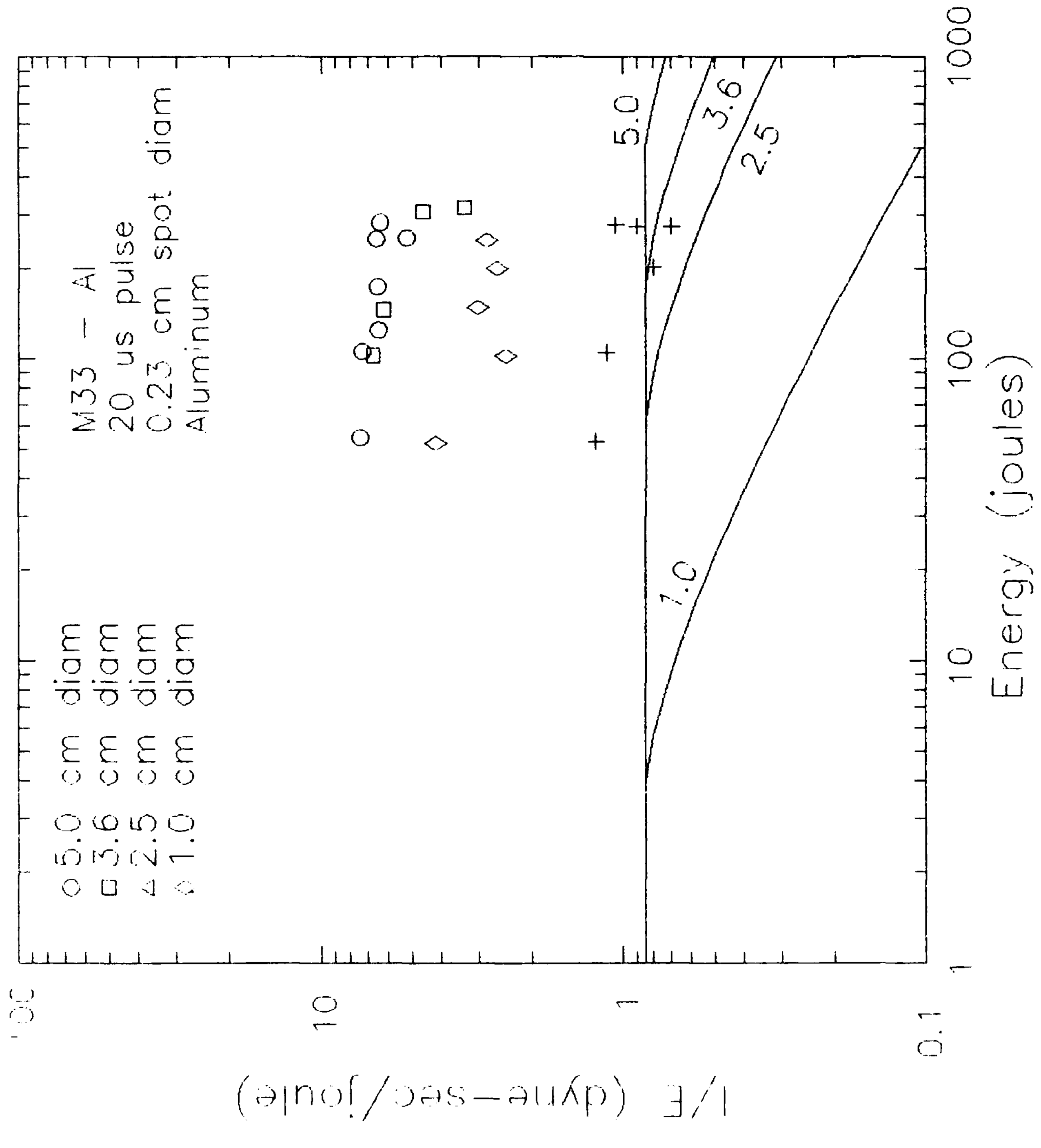
Target dimensions: 0.78, 5, 10, and 19.6 cm^2

Measured quantities: Total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Impulse delivered to aluminum targets 0.78, 5.0, and 19.6 cm^2 in area by a 2×10^{-5}-sec 10.6-μm-wavelength laser pulse laser pulse as a function of beam energy."

Comments: The data here lie well above the values predicted by the Simons model. This is a regime of very small laser spot diameter relative to the pulse duration.



M33 – Al
20 us pulse
0.23 cm spot diam
Aluminum
○ 5.0 cm diam
□ 3.6 cm diam
△ 2.5 cm diam
◇ 1.0 cm diam
5.0
3.6
2.5
1.0
I/E (dyne–sec/joule)
100
10
1
0.1
Energy (joules)
1
10
100
1000

Reference # : B15

Authors : A.I. Barchukov, F.V. Bunkin, V.I. Konov, N.N. Kononov, G.P. Kuz'min, G.A. Mesyats, and N.I. Chapliev

Citation: "'Explosive' mechanism of the pressure exerted on solid targets by CO_2 laser pulses", Sov. J. Quantum Electron. 6, 831-835 (1976)

Institution: P.N. Lebedev Physics Institute, Moscow

Experimental Conditions:

Laser: TEA CO_2

Wavelength: 10.6 μm

Pulse energy: 8 J

Pulse duration: 2 μs

Intensity range: 10 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: 0.15-0.87 cm diameter

Target materials: magnesium

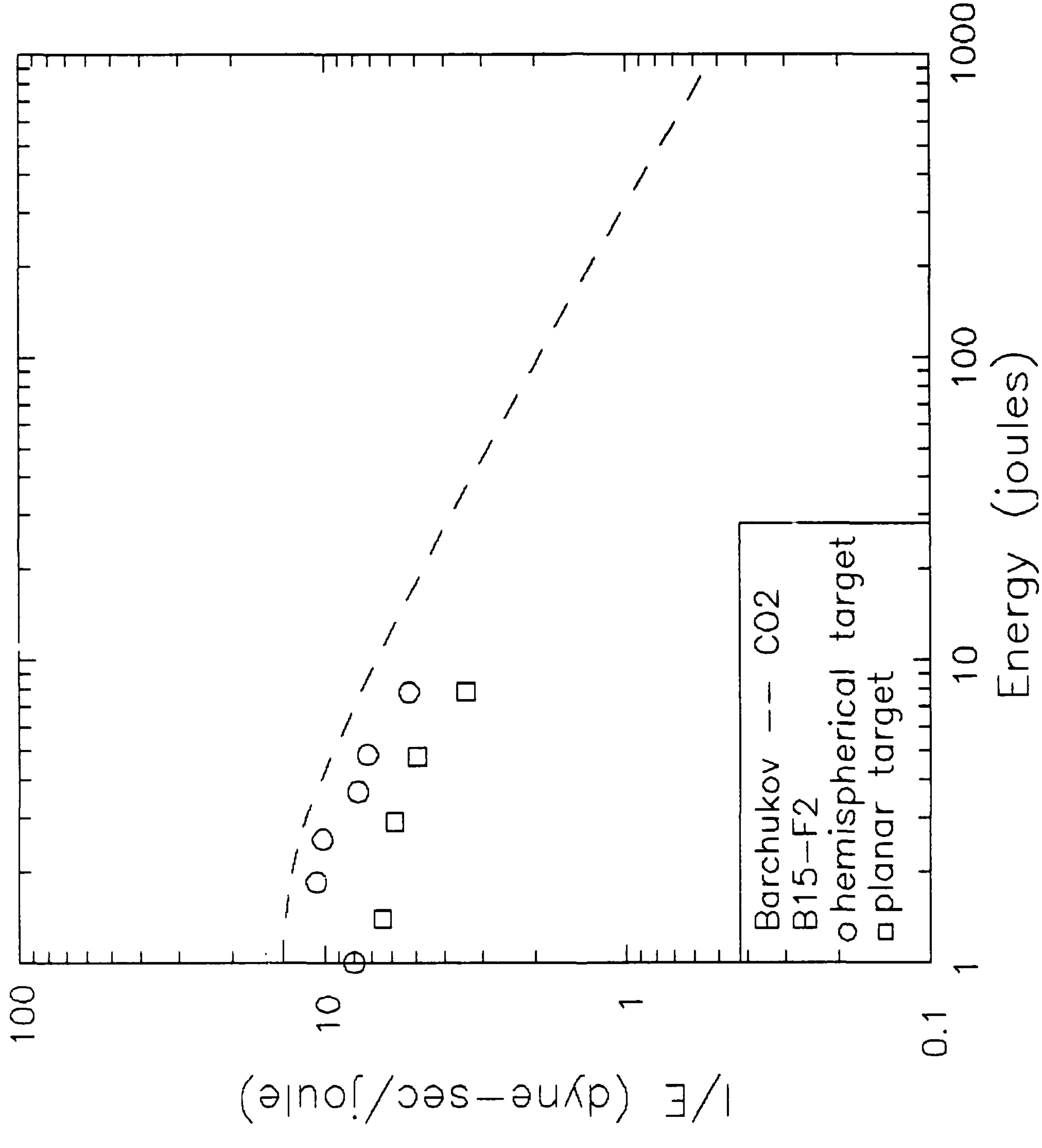
Target dimensions: 1.5 - 2.0 cm^2 area; shape not given

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Dependence of the specific pressure impulse I/E experienced by a target on the energy of laser pulses E reaching a plane magnesium target and a magnesium hemisphere R=5 mm in radius and with approximately the same area."

Comments: Hemispherical (concave towards the laser) targets collect more total impulse from a laser-driven air plasma than a planar target of the same area.


Barchukov — CO2
B15–F2
○ hemispherical target
□ planar target
Energy (joules)
I/E (dyne–sec/joule)
100
10
1
0.1
1
10
100
1000

Reference # : B15 (B15F4)

Authors : A.I. Barchukov, F.V. Bunkin, V.I. Konov, N.N. Kononov, G.P. Kuz'min, G.A. Mesyats, and N.I. Chapliev

Citation: "'Explosive' mechanism of the pressure exerted on solid targets by CO_2 laser pulses", Sov. J. Quantum Electron. 6, 831-835 (1976)

Institution: P.N. Lebedev Physics Institute, Moscow

Experimental Conditions:
- Laser: TEA CO_2
  - Wavelength: 10.6 μm
  - Pulse energy: 50 J
  - Pulse duration: 1 μs
- Intensity range: 5×10^9 W/cm^2
- Atmosphere: 1 atm air

Spot dimensions: 0.36 cm diameter

Target materials: glass and anodized aluminum; or copper-coated glass; the text is obscure

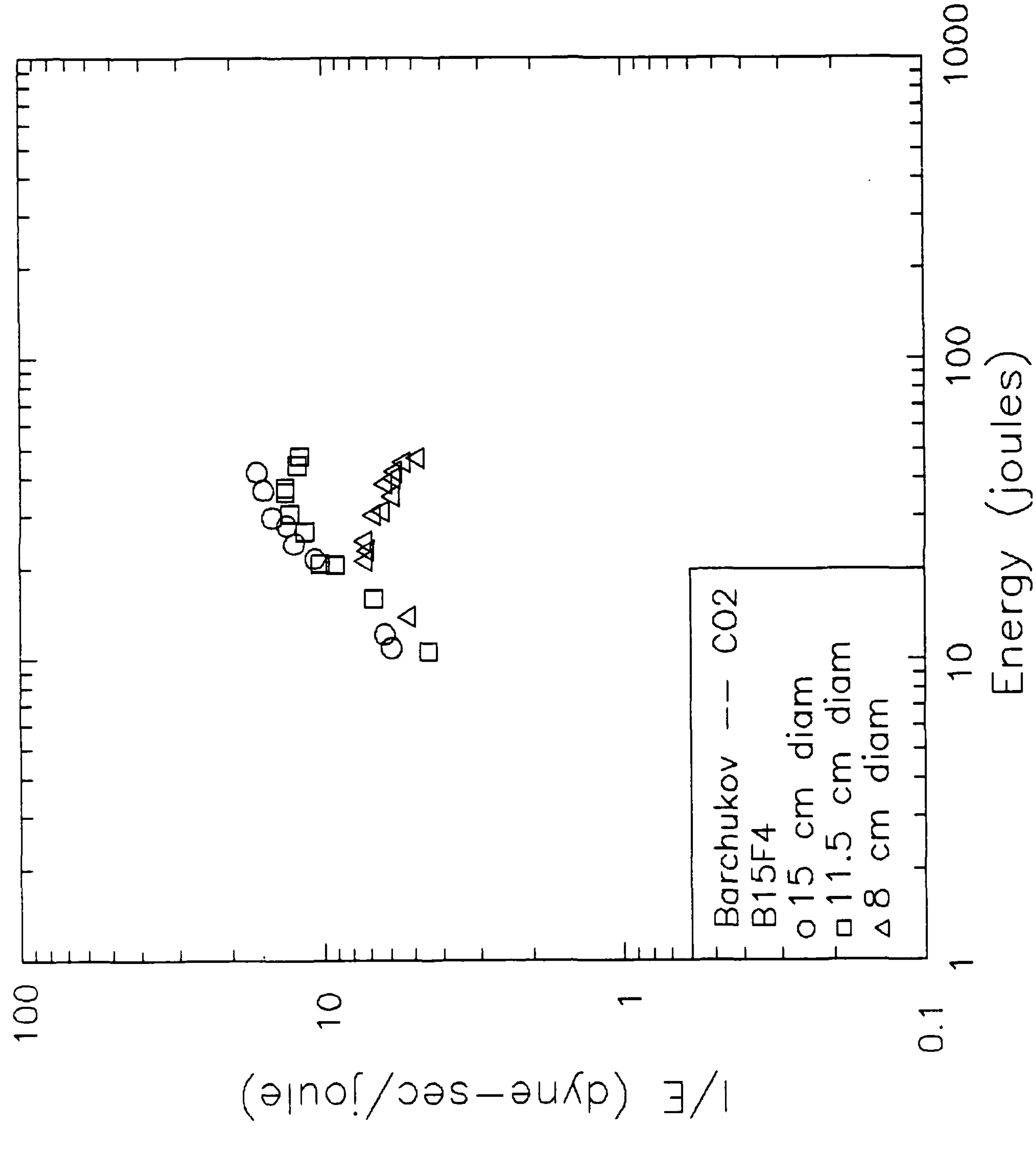
Target dimensions: 8, 11.5, and 15 cm diameter

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Dependences of the specific pressure impulse I/E on the total energy in a laser pulse E for three values of the hemisphere diameter D."

Comments: Larger hemispheres develop greater total delivered impulse. The laser pulse was focussed at the center of curvature of the hemisphere, or focussed by the hemisphere itself at approximately half the sphere radius.



Barchukov -- CO2
B15F4
○ 15 cm diam
□ 11.5 cm diam
△ 8 cm diam
100
10
1
0.1
I/E (dyne-sec/joule)
1
10
100
1000
Energy (joules)

Reference # : T4

Authors : Francis W. French, James P. Reilly, and Glenn W. Zeiders

Citation: "Single pulse CO_2 laser atmospheric impulse measurements and analyses", WJSA-TR-83-217 (February 1983)

Institution: W.J. Schafer Associates, Chelmsford MA

Experimental Conditions:

Laser: UV-preionized electron-beam CO_2

Wavelength: 10.6 μm

Pulse energy: 120 J

Pulse duration: 100 ns

Intensity range: 5×10^7 - 2×10^9 W/cm^2

Atmosphere: 1 atm air

Spot dimensions: 1.0, 1.7, and 2.7 cm diam.

Target materials: aluminum, carbon (Grafoil)

Target dimensions: 4 and 8 cm diam

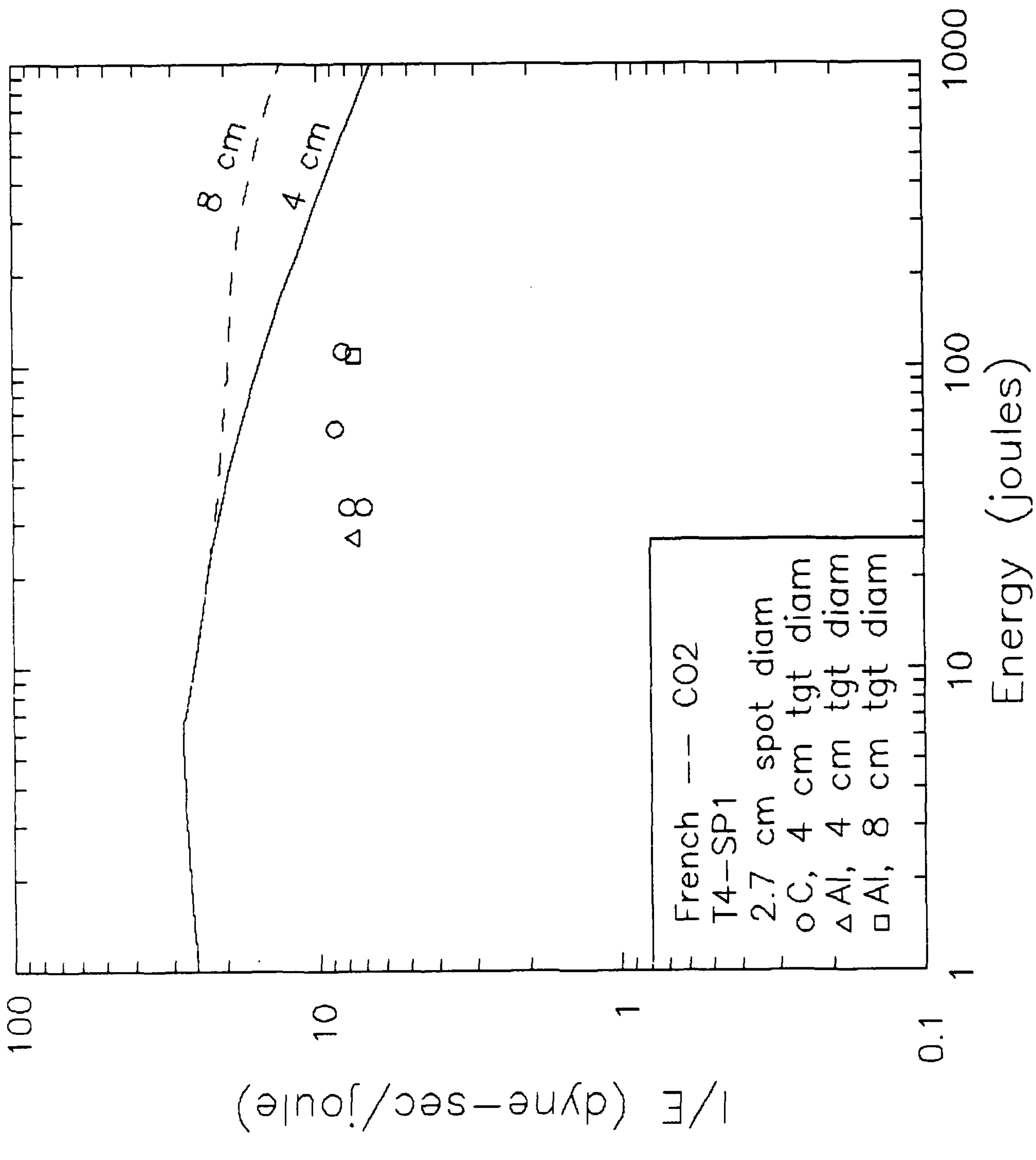
Measured quantities: total impulse

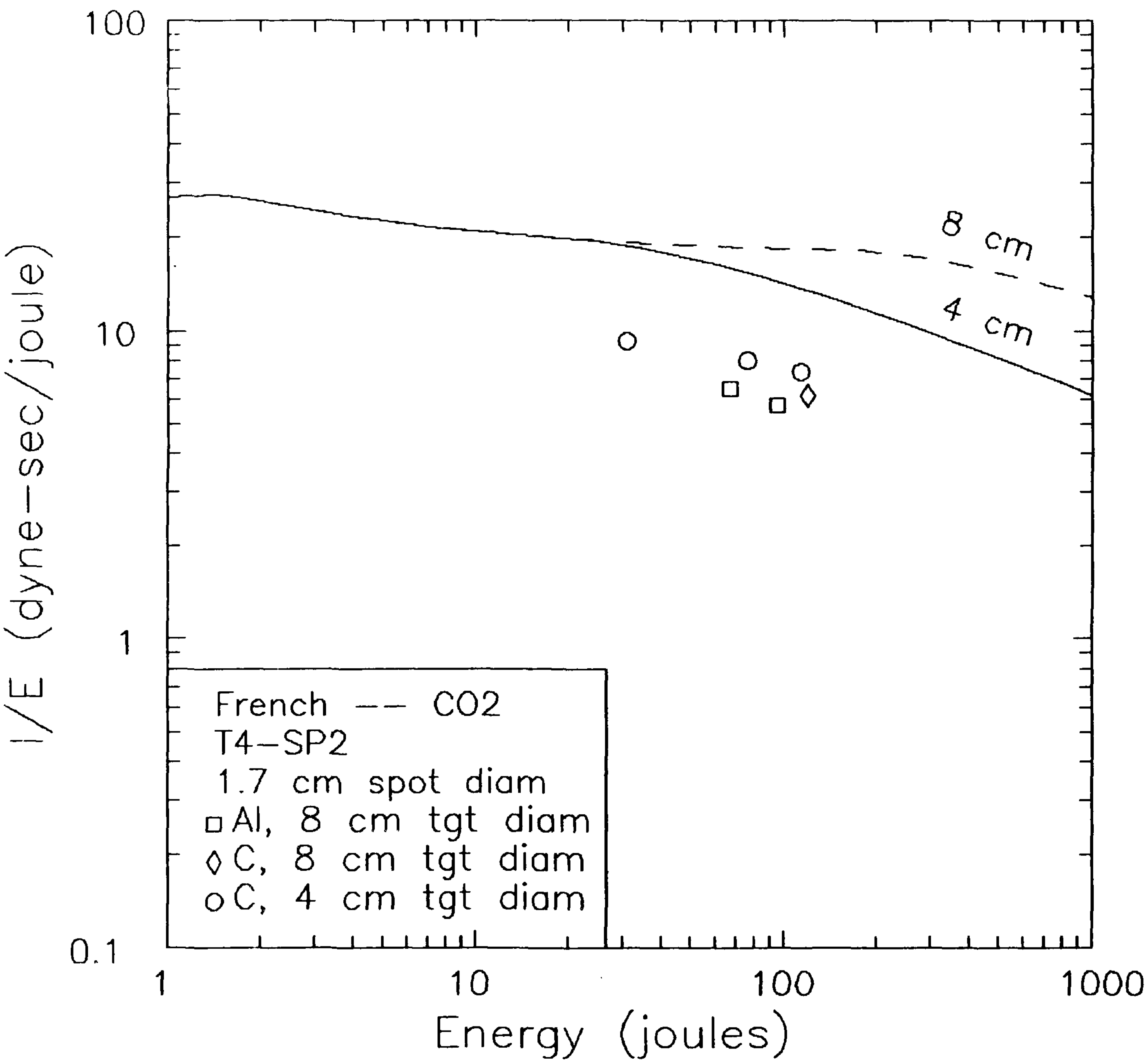
Measurement technique(s): ballistic pendulum

Table caption: "Pendulum test results"

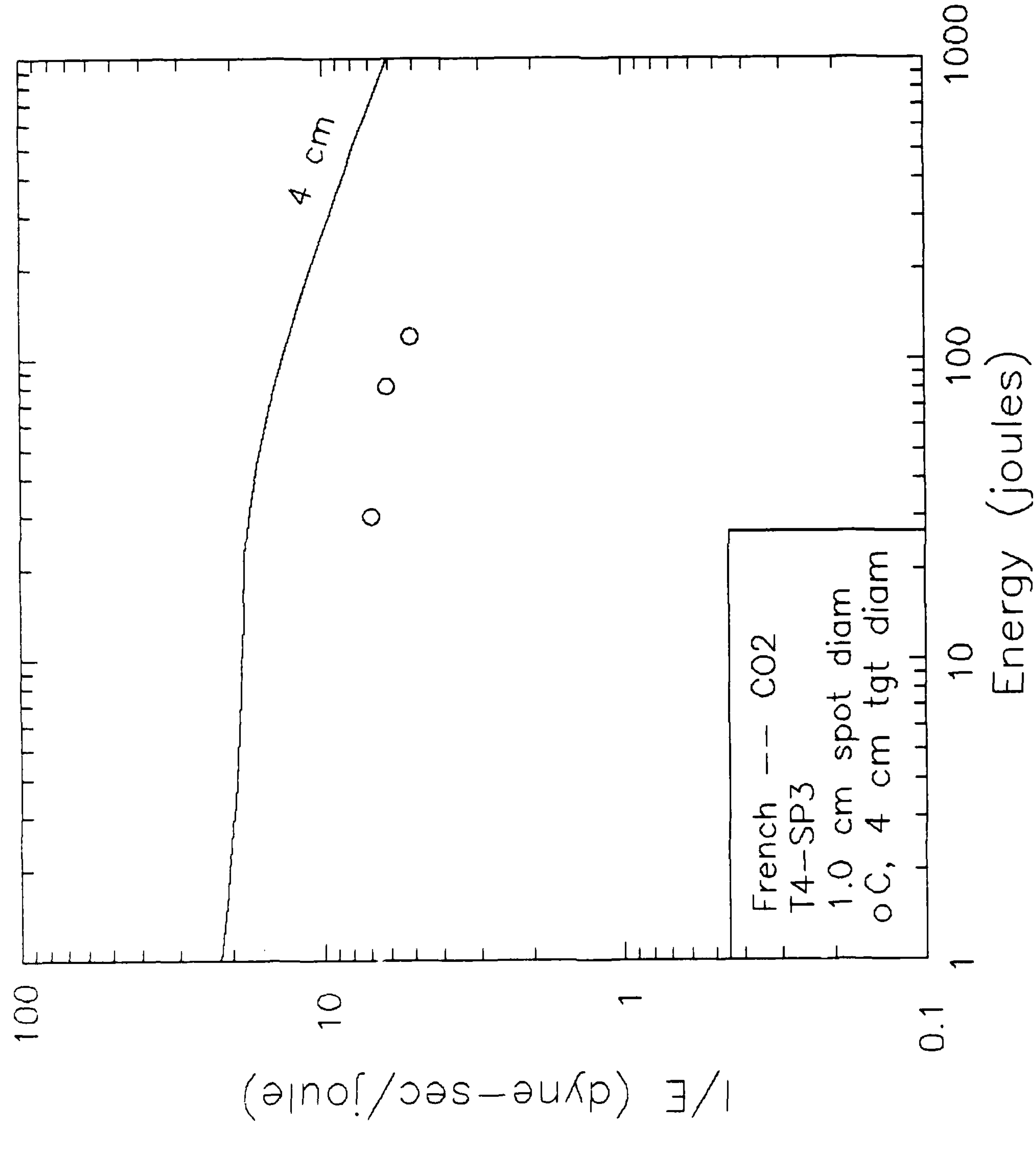
Comments: The theory line lies significantly higher than the data. This may be due to the failure of the model for targets so much larger than the laser spots that the weak limit of the blast wave is important. In this limit the model, which neglects the back pressure of the atmospher, will predict higher values than will in fact obtain. Both the 4 cm and 8 cm diameter targets were large enough here to capture the entire blast wave generated by the laser pulse.

As in other experiments in air at laser intensities well above plasma ignition threshold, the target material has little effect on the impulse coupling. "Grafoil" is a form of graphite rolled into thin (5 mils) sheets, and is visually shiny. It is a product of the Union Carbide Co.


French -- CO2
T4-SP1
2.7 cm spot diam
○ C, 4 cm tgt diam
△ Al, 4 cm tgt diam
□ Al, 8 cm tgt diam
8 cm
4 cm
I/E (dyne-sec/joule)
Energy (joules)
100
10
1
0.1
1
10
100
1000



I/E (dyne-sec/joule)
100
10
1
0.1
1
10
100
1000
Energy (joules)
8 cm
4 cm
French -- CO2
T4-SP2
1.7 cm spot diam
□ Al, 8 cm tgt diam
◊ C, 8 cm tgt diam
○ C, 4 cm tgt diam


4 cm
French — CO2
T4–SP3
1.0 cm spot diam
o C, 4 cm tgt diam
Energy (joules)
I/E (dyne–sec/joule)
1
10
100
1000
0.1
1
10
100

Reference # : B27

Authors : S.K. Searles and C.W. Rector

Citation: "Impulse coupling of intense laser pulses with 6061-T6 aluminum", unpublished report (undated)

Institution: Naval Research Laboratory, Washington DC, and U.S. Naval Academy, Annapolis MD

Experimental Conditions:

Laser: electron beam pumped pulsed HF/DF chemical laser ("Mjollnir")

Wavelength: 2.7 μm primary, other lines to 3.2 μm

Pulse energy: approx. 2 kJ

Pulse duration: 1.6-1.8 μs fwhm

Intensity range: 1×10^8 - 4×10^9 W/cm^2

Atmosphere: 1 atm air

Spot dimensions: rectangular beam (4:3 aspect ratio) with rectangular hole due to output coupler; spot areas (excluding hole) 0.41 to 12 cm^2

Target materials: bead-blasted aluminum (6061-T6)

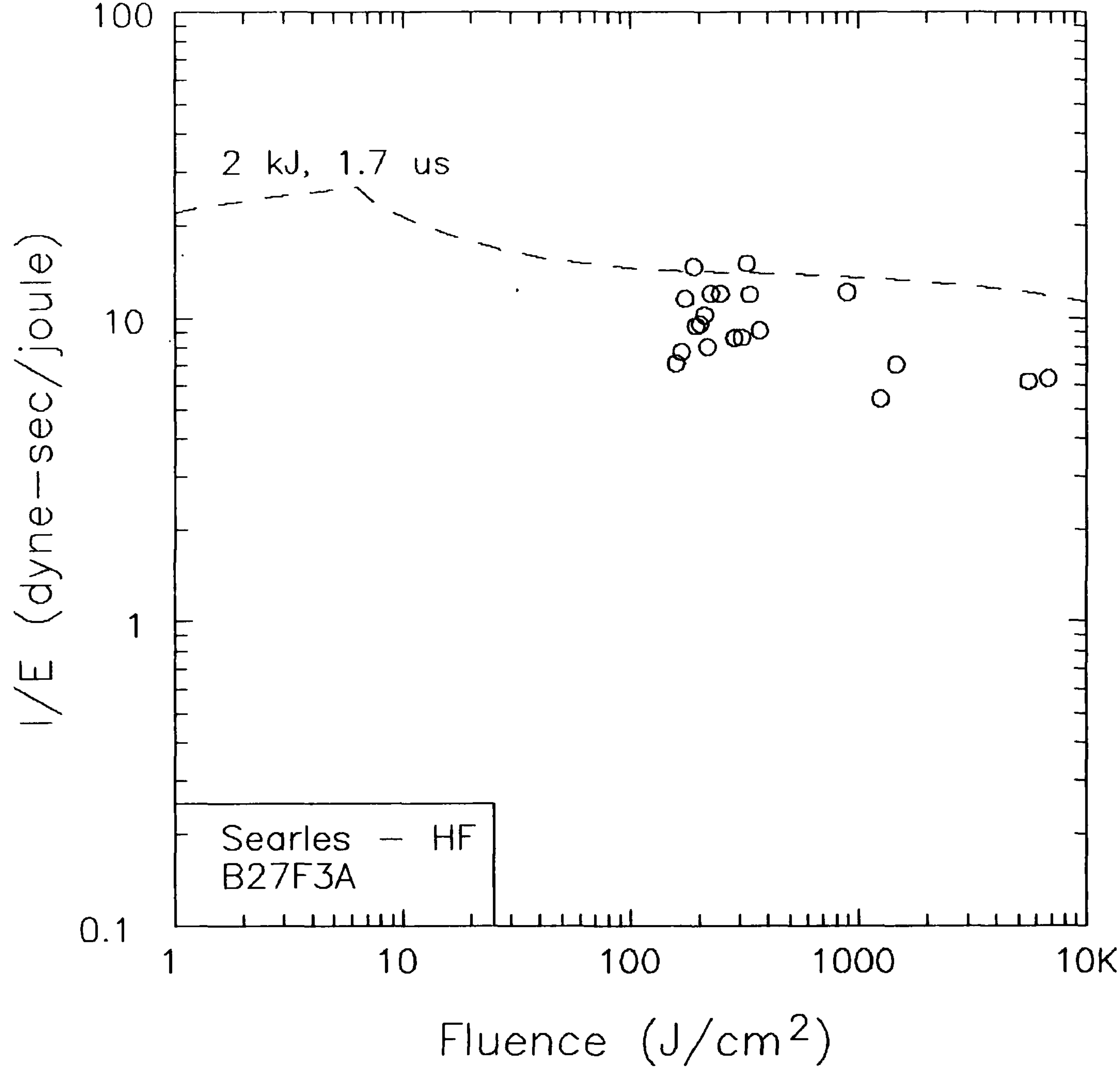
Target dimensions: 10x11.4x0.08128 cm

Measured quantities: total impulse

Measurement technique(s): target velocity measurement with mutual inductance proximeter

Figure caption: none.

Comments: This represents perhaps the optimal condition for impulse coupling, large spot dimensions, intensities sufficient for full plasma development, and high fluence levels. The coupling is among the highest under any conditions, about 10 dyne-seconds per joule.



2 kJ, 1.7 us
Searles – HF
B27F3A
I/E (dyne–sec/joule)
Fluence (J/cm2)
100
10
1
0.1
1
10
100
1000
10K

Reference # : B28

Authors : C.L. Bohn, M.D. Stephen, F. Eng, J.C. Souders, G.A. Brost, T.F. Deaton, B.W. Duvall, and J.T. Tinsley

Citation: "Mechanical coupling of an iodine laser pulse incident obliquely on aluminum", SPIE Vol. 540, Southwest Conference on Optics (1985)

Institution: U.S. Air Force Academy, Colorado Springs CO; Kaman Sciences Corporation, Colorado Springs CO

Experimental Conditions:
- Laser: atomic-iodine photodisassociation
  - Wavelength: 1.315 μm
  - Pulse energy: 5 J
  - Pulse duration: 15 μs (full width)
- Intensity range: 10 - 80 MW/cm^2 (peak)
- Atmosphere: 1 atm air

Spot dimensions: 0.075 cm diam (1/e value)

Target materials: aluminum (Alclad 2024)

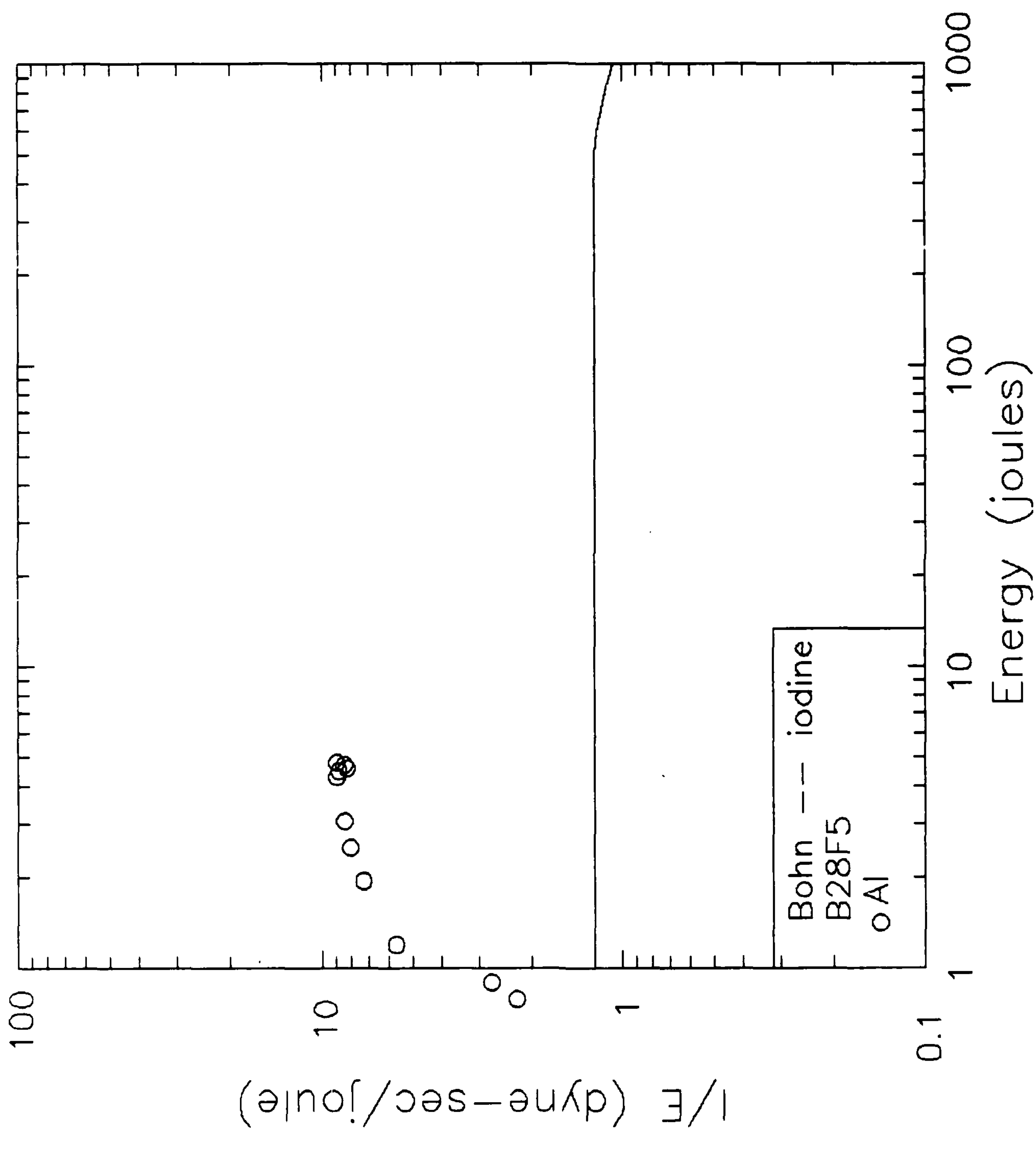
Target dimensions: 5.08 cm square

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum with optical displacement transducer

Figure caption: "I/E vs. [peak laser intensity] at normal incidence."

Comments: These impulse data lie far above the model predictions, possibly a consequence of the very small spot dimensions and relatively long pulse.



I/E (dyne-sec/joule)
100
10
1
0.1
1
10
100
1000
Energy (joules)
Bohn -- iodine
B28F5
○ Al

Reference # : B28

Authors : C.L. Bohn, M.D. Stephen, F. Eng, J.C. Souders, G.A. Brost, T.F. Deaton, B.W. Duvall, and J.T. Tinsley

Citation: "Mechanical coupling of an iodine laser pulse incident obliquely on aluminum", SPIE Vol. 540, Southwest Conference on Optics (1985)

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Experimental Conditions:
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  - Pulse energy: 5 J
  - Pulse duration: 15 μs (full width)
- Intensity range: 10 - 80 MW/cm^2 (peak)
- Atmosphere: 1 atm air

Spot dimensions: 0.075 cm diam (1/e value)

Target materials: aluminum (Alclad 2024)

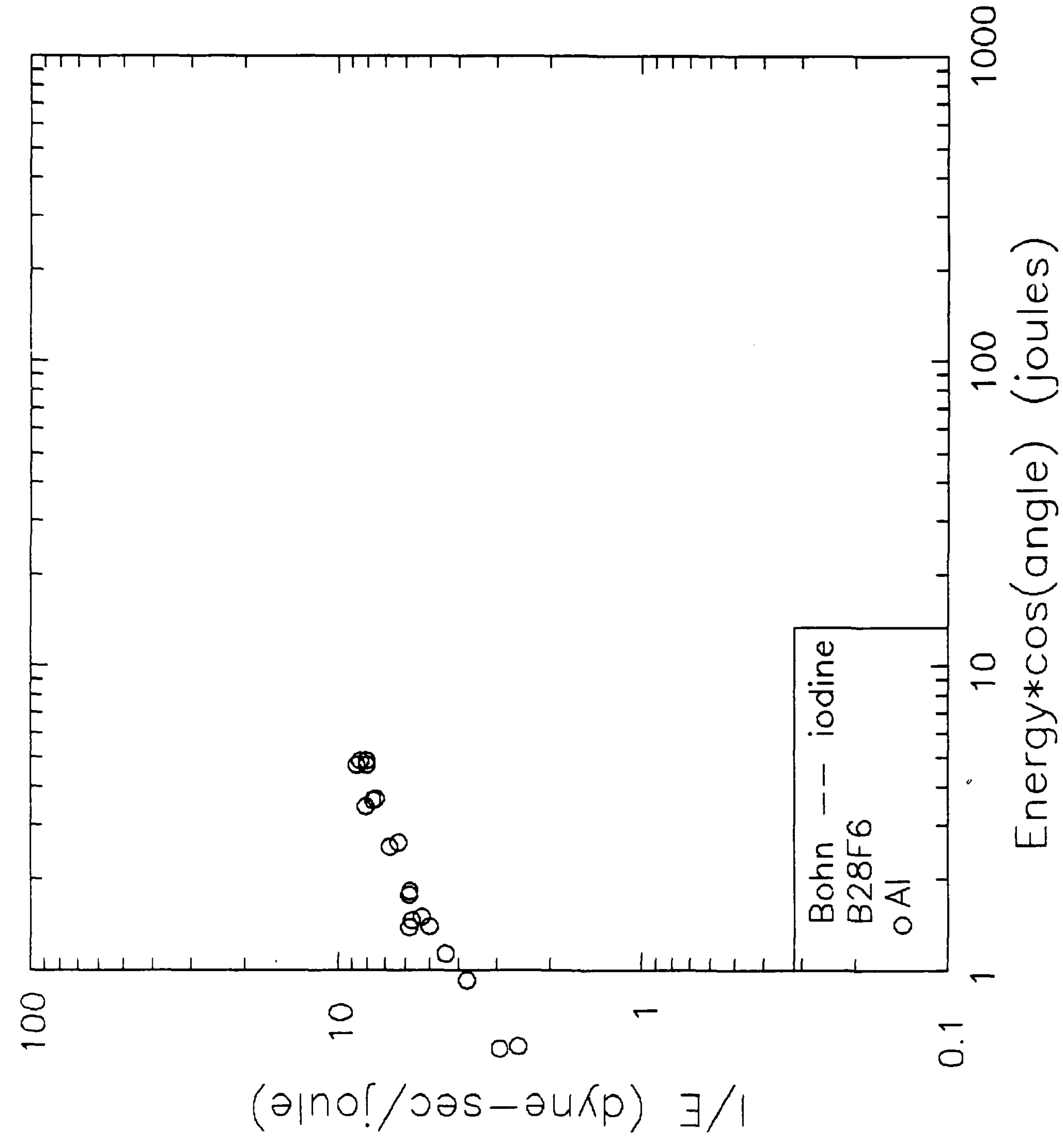
Target dimensions: 5.08 cm square

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum with optical displacement transducer

Figure caption: "I/E vs. [peak laser intensity]*cos(angle of incidence). The solid line [not shown here] indicates a slope of 1/3."

Comments: The decline in I/E at large oblique angles (greater than 77°) is attributed to spreading of the blast wave over the target edges, as the spot stretches in one dimension to approach those edges. The decline at smaller angles is not understood. "We conclude from the present investigation that cylindrical blast-wave theory cannot be applied indiscriminately to model the total impulse delivered by an intense laser pulse of long duration and small spot size incident obliquely on a metal surface."



Bohn -- iodine
B28F6
o Al
Energy*cos(angle) (joules)
I/E (dyne-sec/joule)
100
10
1
0.1
1000

Reference # : B20

Authors : V.A. Batanov, F.V. Bunkin, A.M. Prokhovov and V.B. Fedorov

Citation: "Evaporation of metallic targets caused by intense optical radiation", Sov. Phys. JETP 36, 311-322 (1973)

Institution: P.N. Lebedev Physics Institute, USSR

Experimental Conditions:

Laser: Nd:glass

Wavelength: 1.06 μm

Pulse energy: 10 kJ

Pulse duration: 800 μs

Intensity range: 2×10^5 - 3×10^7 W/cm^2

Atmosphere: 1 atm air

Spot dimensions: variable, "not less than 0.7 cm [diameter]"

Target materials: Aluminum, iron, lead, Wood's alloy, bismuth

Target dimensions: not given

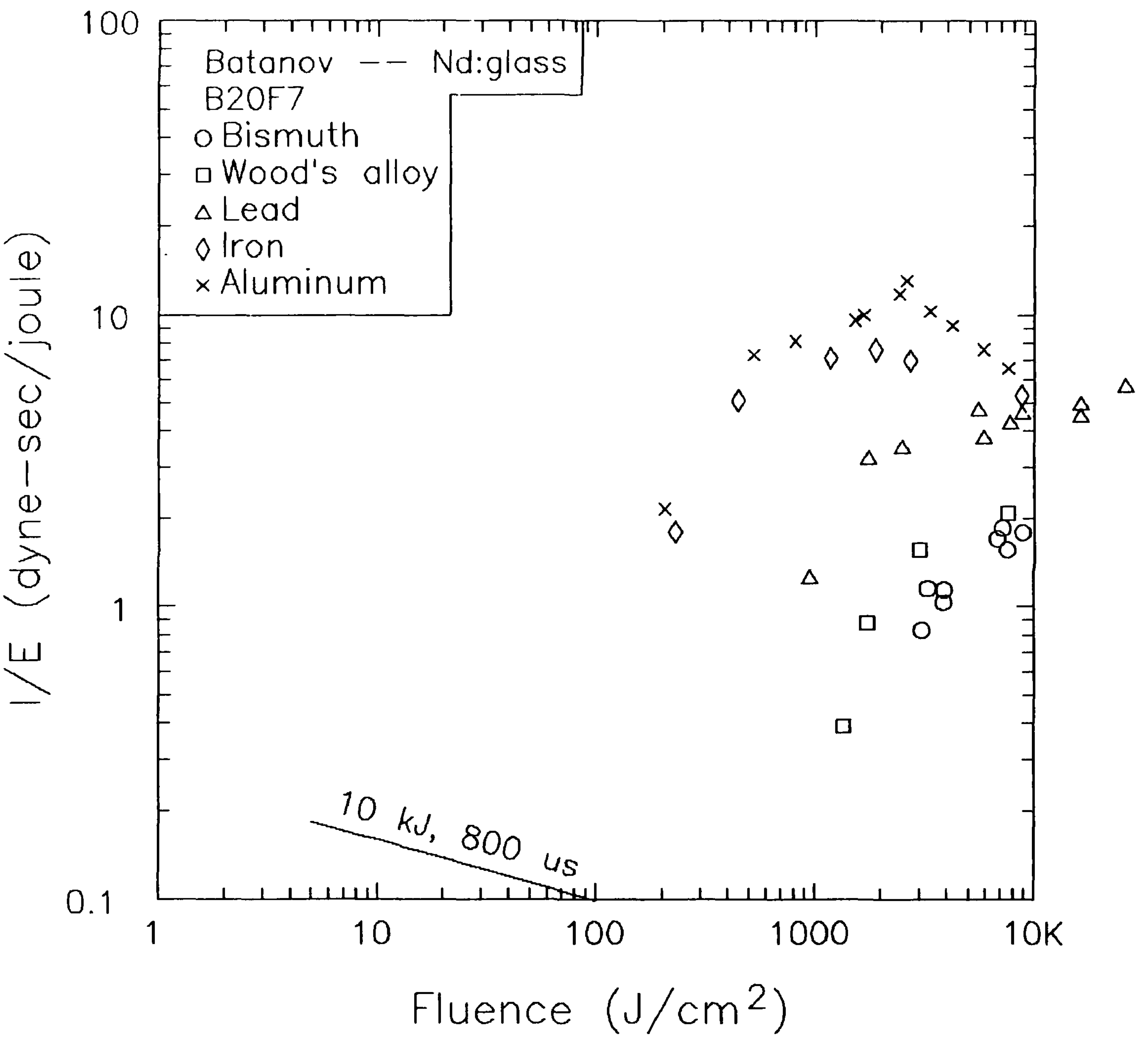
Measured quantities: total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Experimental plot of the relative recoil momentum J/E0 against the incident-radiation intensity I0 for aluminum, iron, lead, Wood's alloy, and bismuth."

Comments: This illustrates impulse coupling in a regime of pure metal ablation and ejection. The coupling can be quite high under these conditions, comparable to the higher values obtained for air-plasma impulse delivery. The authors attribute the coupling to the conversion of the metal to a laser-transparent dielectric under the intense pressure and heating of the laser beam. Whether the high coupling is proof of this conversion, or is merely the consequence of high impulse production by solid mass ejection, is open to speculation. The ejection of molten mass at low velocities, i.e. laser drilling, is a very energy-efficient means of impulse production.

The fragmentary curve indicates the coupling predicted for air blast wave impulse delivery.


Batanov -- Nd:glass
B20F7
o Bismuth
□ Wood's alloy
△ Lead
◊ Iron
× Aluminum
10 kJ, 800 us
I/E (dyne-sec/joule)
100
10
1
0.1
1
10
100
1000
10K
Fluence (J/cm2)

Reference # : B4

Authors : Ralph R. Rudder, Jay A. Howland, and Arnold L. Augustoni

Citation: unpublished report

Institution: Air Force Weapons Laboratory

Experimental Conditions:

Laser: Nd:glass (amplified spontaneous emission type)

Wavelength: 1.06 μm

Pulse energy: 100 J

Pulse duration: 1.1 μs

Fluence range: 8 - 120 J/cm^2

Atmosphere: 1 atm air and vacuum (25 μm Hg)

Spot dimensions: 0.92 cm diam

Target materials: Titanium 6Al-4V

Target dimensions: 1.59, 2.54, 5.08 cm diam disks

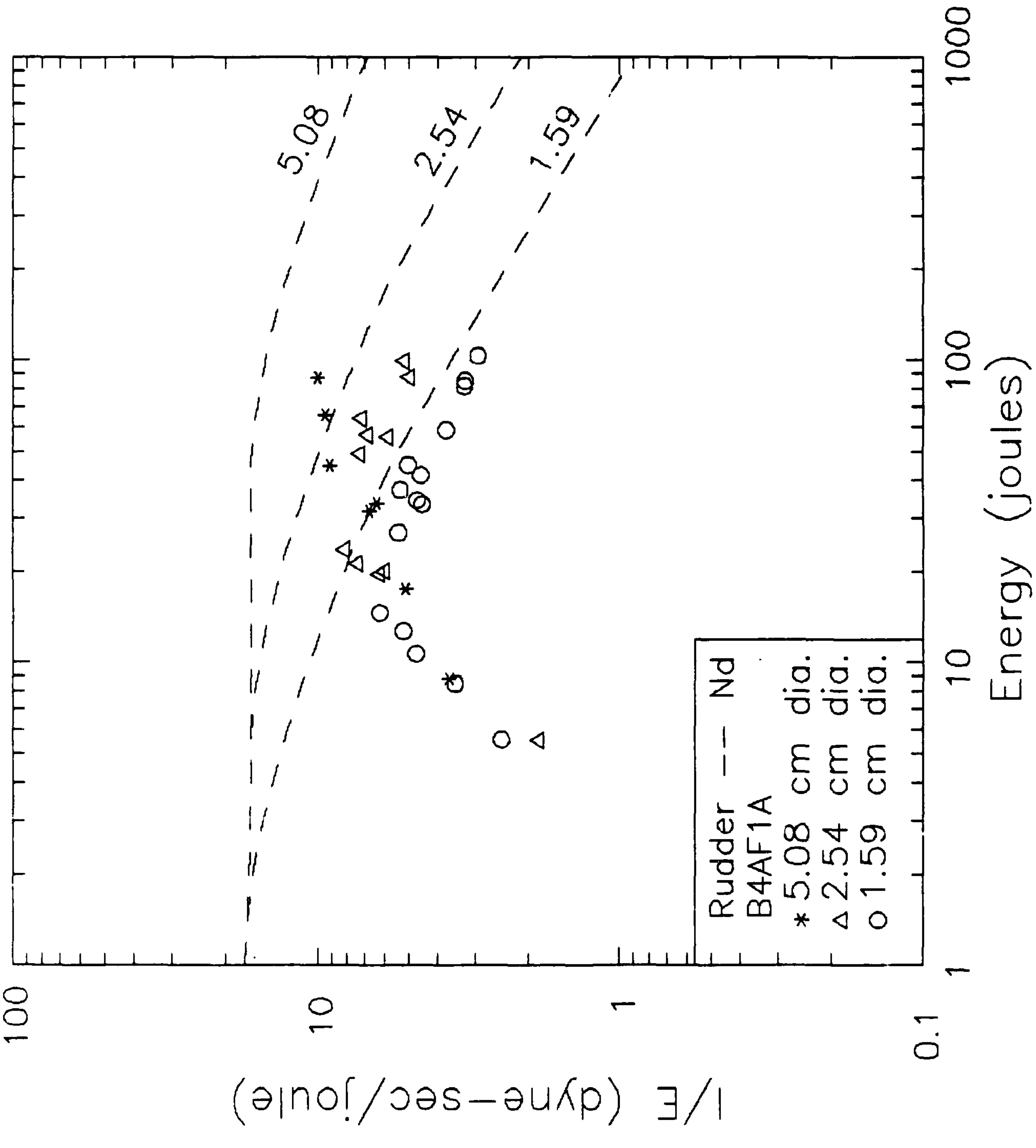
Measured quantities: Impulse

Measurement technique(s): LVT

Figure caption: "Total impulse, measured with LVT gauge, imparted to titanium (6Al-4V) discs of diameter 3/8-inch, 1-inch, and 2 inches, versus laser fluence . . ."

Comments: "These experiments have shown for 1.06-μ pulses of duration 1.1 μs that the momentum transferred to titanium targets increases with increasing target diameter for fluxes greater than about 3x10^7 W/cm2. No similar target-size dependence was noted for vacuum interactions, and the momentum transfer was reduced. All of these results can be interpreted via a theoretical treatment based on a laser-driven absorption wave and a subsequent air blast wave. However, adequate numerical agreement with the experiments is not yet available."

The Simons model calculations are in fair agreement with these data. At low laser intensities the effects of plasma threshold are evident.



Rudder -- Nd
B4AF1A
* 5.08 cm dia.
Δ 2.54 cm dia.
o 1.59 cm dia.
5.08
2.54
1.59
Energy (joules)
I/E (dyne-sec/joule)
1
10
100
1000
0.1

Reference # : B39

Authors : R.R. Rudder

Citation: "Momentum transfer to solid target discs by pulsed one-micron radiation", AFWL-TR-73-273 (December 1973)

Institution: Air Force Weapons Laboratory, Albuquerque NM

Experimental Conditions:
- Laser: Nd:glass, amplified spontaneous emission type
  - Wavelength: 1.06 μm
  - Pulse energy: 125 J
  - Pulse duration: 1 - 100 μs
- Intensity range: 1 - 300 MW/cm^2
- Atmosphere: 1 atm air

Spot dimensions: 0.25 cm^2 (0.56 cm diam)

Target materials: Titanium 6Al-4V, aluminum (2024-T3), graphite (GTA Grafoil)

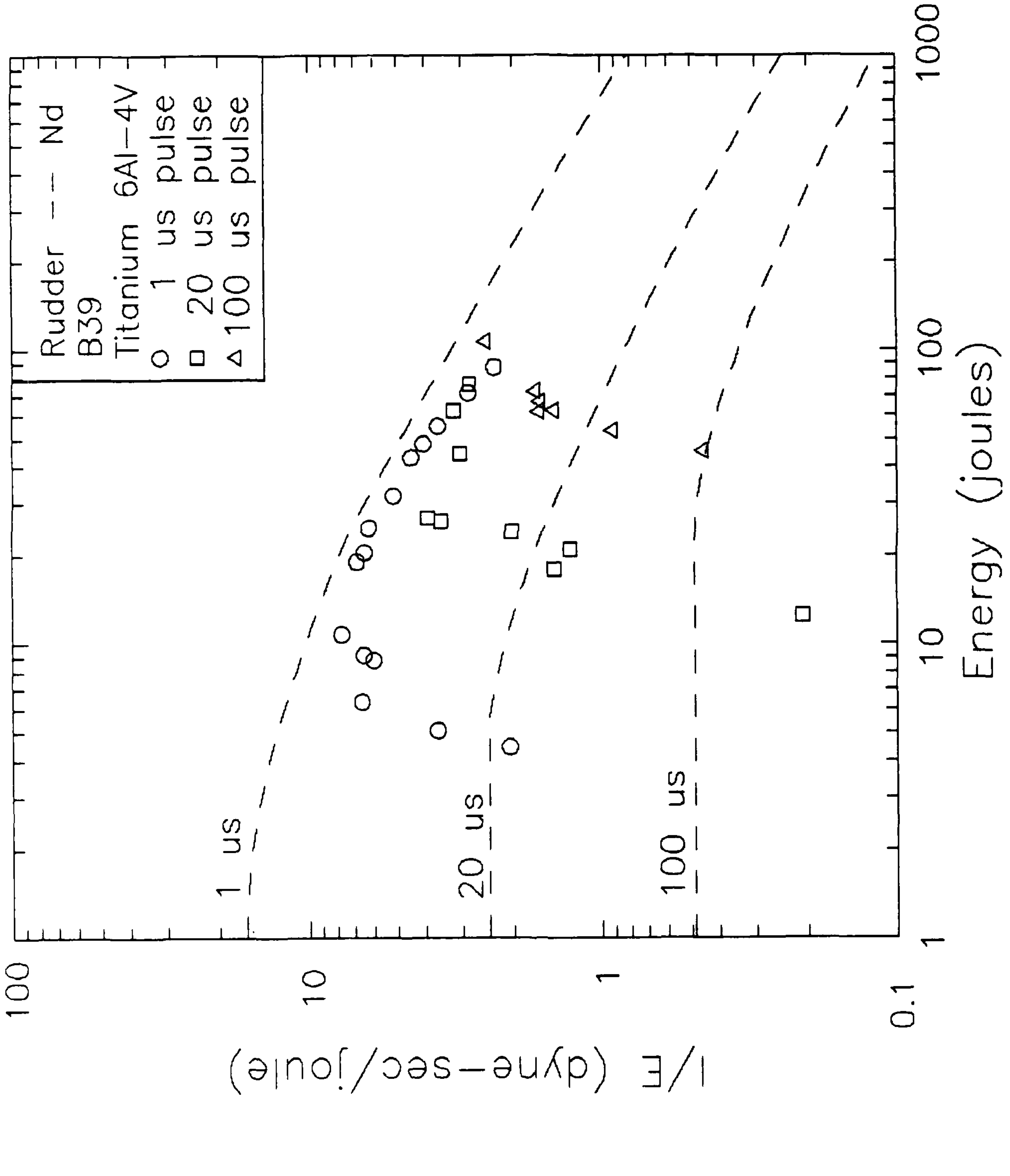
Target dimensions: 1.59 cm diam

Measured quantities: total impulse

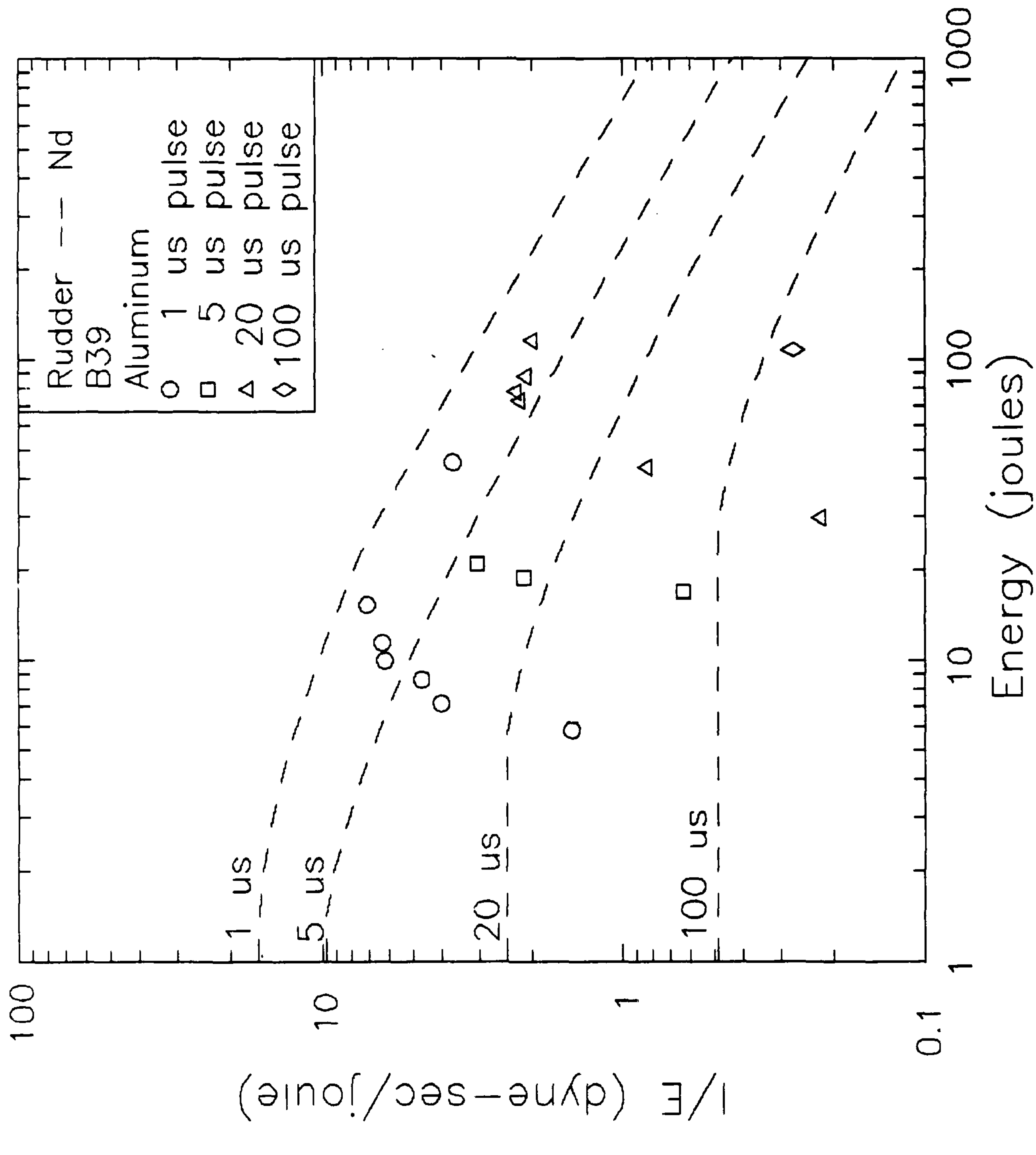
Measurement technique(s): linear velocity transducer

Figure captions: "Momentum transfer versus incident energy for 0.625-inch diameter titanium (6Al4V) discs. . ."; Momentum transfer versus incident energy for 0.625-inch diameter aluminum (2024-T3) discs. . ."; Momentum transfer versus incident energy for 0.625-inch diameter graphite discs. . ."

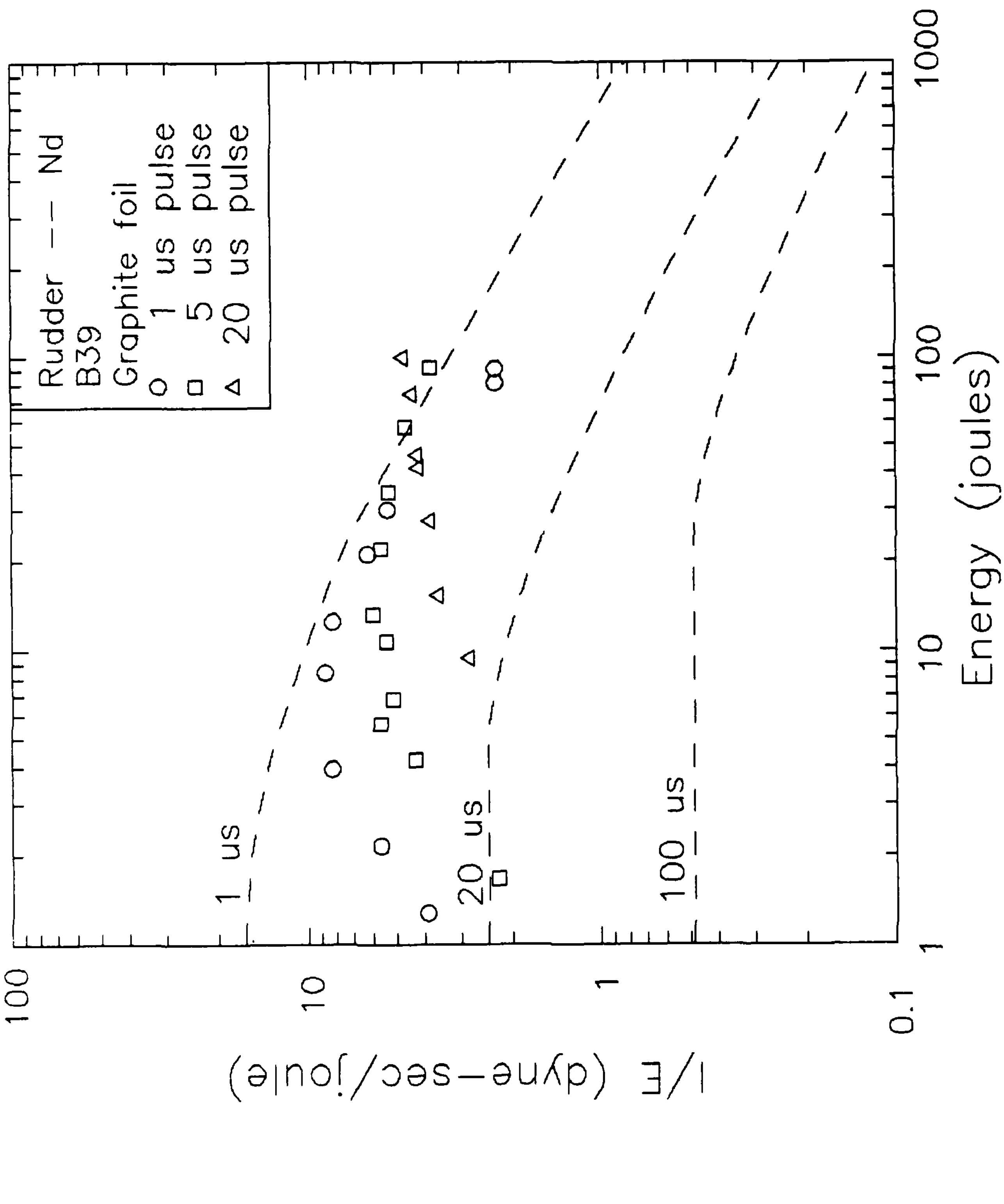
Comments: Several different phenomena are evident in this excellent set of data. Increasing the pulse duration for a given pulse energy plainly shifts the threshold for plasma formation, apparent as varying locations for the rise of impulse coupling on the energy axis. Differences between materials in ignition threshold are also apparent, the order of difficulty in plasma ignition being graphite, titanium, and aluminum, corresponding essentially to the trend in metal absorptance at this wavelength. The influence of pulse duration appears from the data to be very modest, considerably less than predicted by the Simons model. As is apparent on other sets of data, the model works reasonably well for short pulses and high intensities, but severely underpredicts the impulse for long pulses.



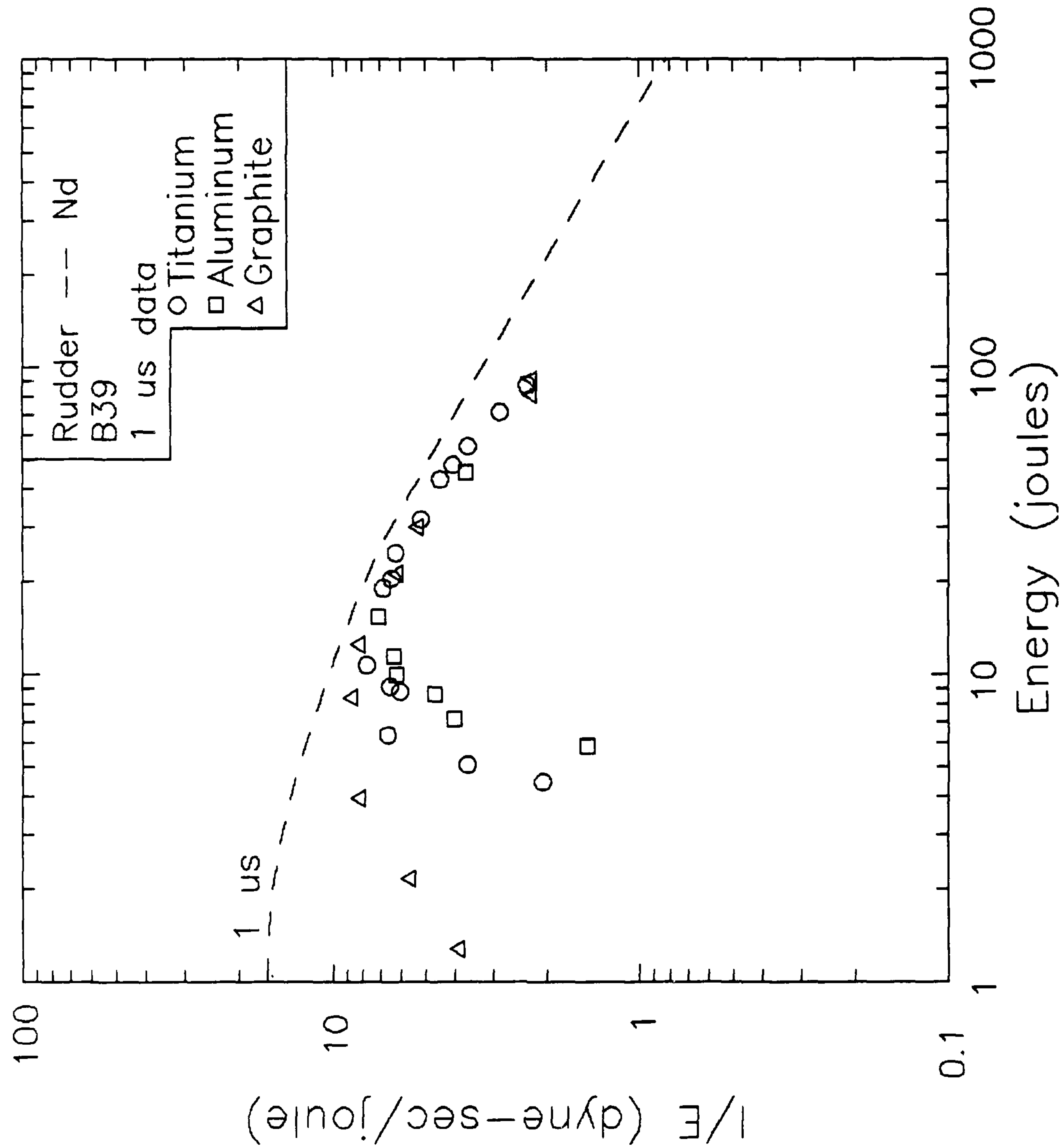
Rudder --- Nd
B39
Titanium 6Al-4V
○ 1 us pulse
□ 20 us pulse
△ 100 us pulse
1 us
20 us
100 us
I/E (dyne-sec/joule)
100
10
1
0.1
1
10
100
1000
Energy (joules)

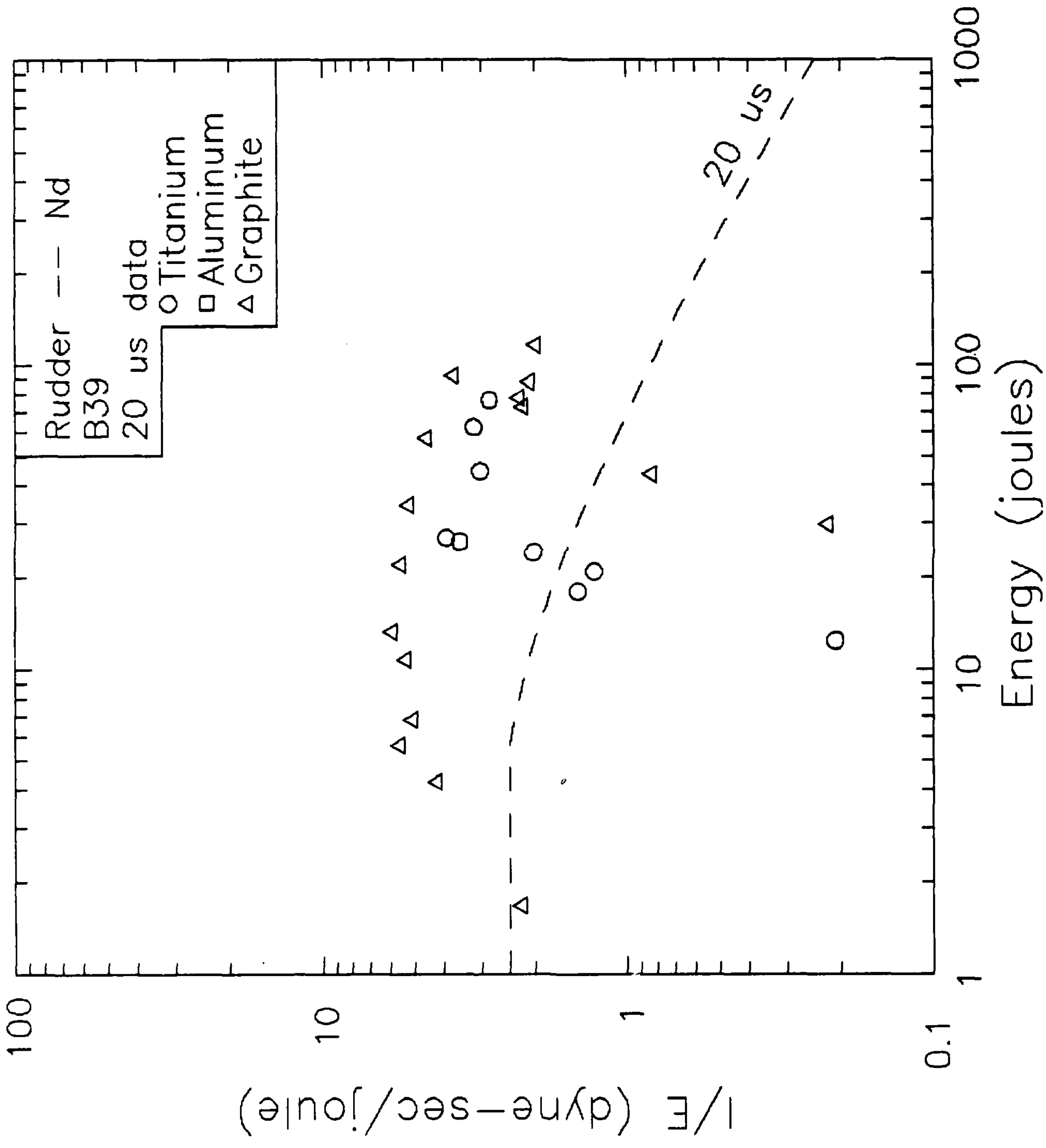


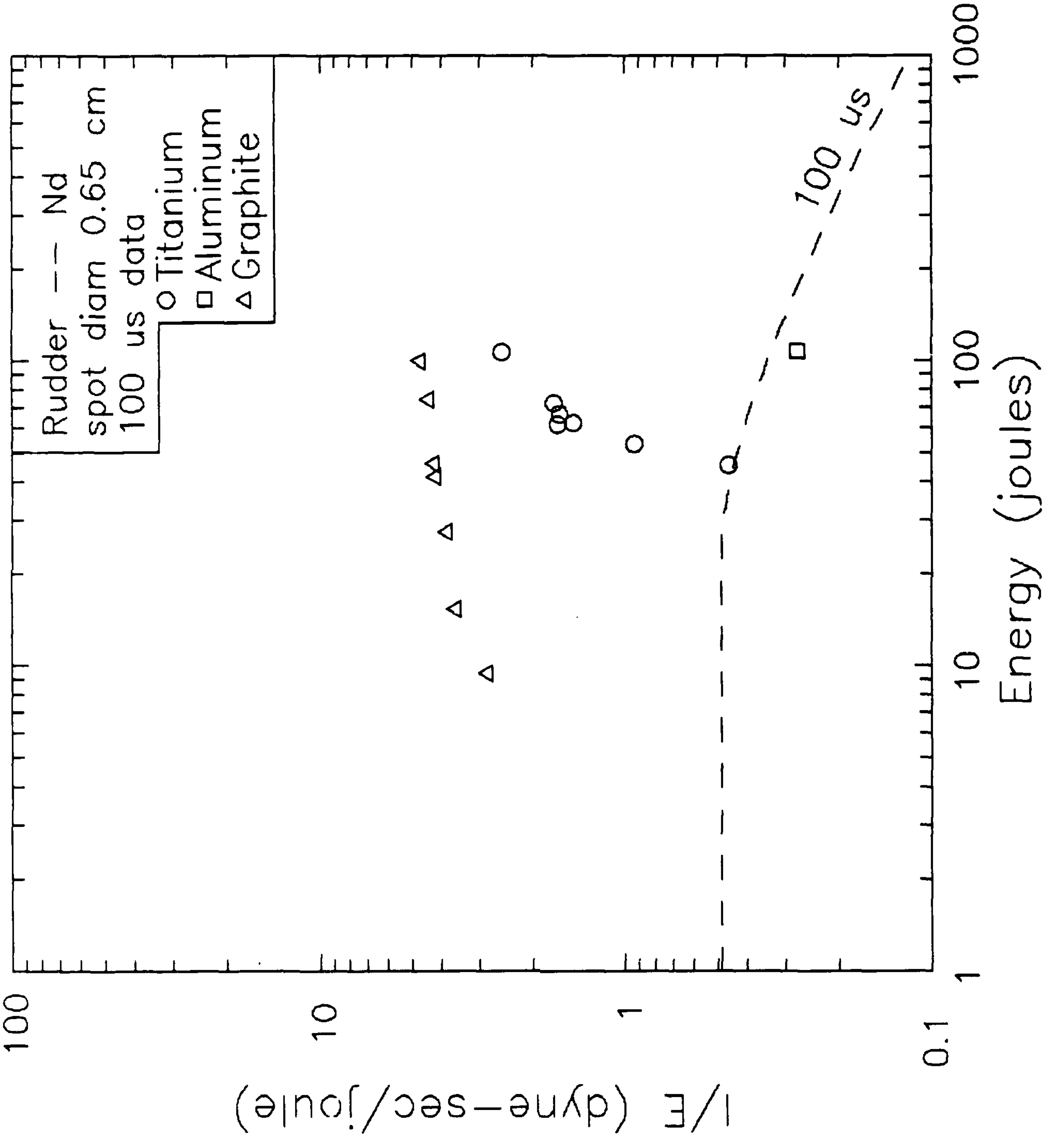
Rudder — Nd
B39
Aluminum
1 us pulse
5 us pulse
20 us pulse
100 us pulse
1 us
5 us
20 us
100 us
I/E (dyne-sec/joule)
Energy (joules)
100
10
1
0.1
1
10
100
1000



Rudder -- Nd
B39
Graphite foil
1 us pulse
5 us pulse
20 us pulse
1 us
20 us
100 us
Energy (joules)
I/E (dyne-sec/joule)
100
10
1
0.1
1000


Rudder --- Nd
B39
1 us data
Titanium
Aluminum
Graphite
1 us
I/E (dyne-sec/joule)
100
10
1
0.1
Energy (joules)
1
10
100
1000


Rudder —— Nd
B39
20 us data
Titanium
Aluminum
Graphite
20 us
100
10
1
0.1
I/E (dyne–sec/joule)
1
10
100
1000
Energy (joules)


Rudder -- Nd
spot diam 0.65 cm
100 us data
Titanium
Aluminum
Graphite
100 us
I/E (dyne-sec/joule)
100
10
1
0.1
1
10
100
1000
Energy (joules)

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Reference # : B32

Authors: S.A. Metz

Citation: "Impulse loading of targets by subnanosecond laser pulses", Appl. Phys. Lett. 22, 211-213 (1973)

Institution: Naval Research Laboratory, Washington DC

Experimental Conditions:
Laser: Nd:YAG
Wavelength: 1.06 μm
Pulse energy: 25 J
Pulse duration: 0.25 ns
Intensity range: to 1.4×10^{10} W/cm^2
Atmosphere: 1 atm air, and vacuum (under 100 μm Hg)

Spot dimensions: 1.5 cm diam

Target materials: aluminum (1100), carbon (POCO AXF-5Q graphite)

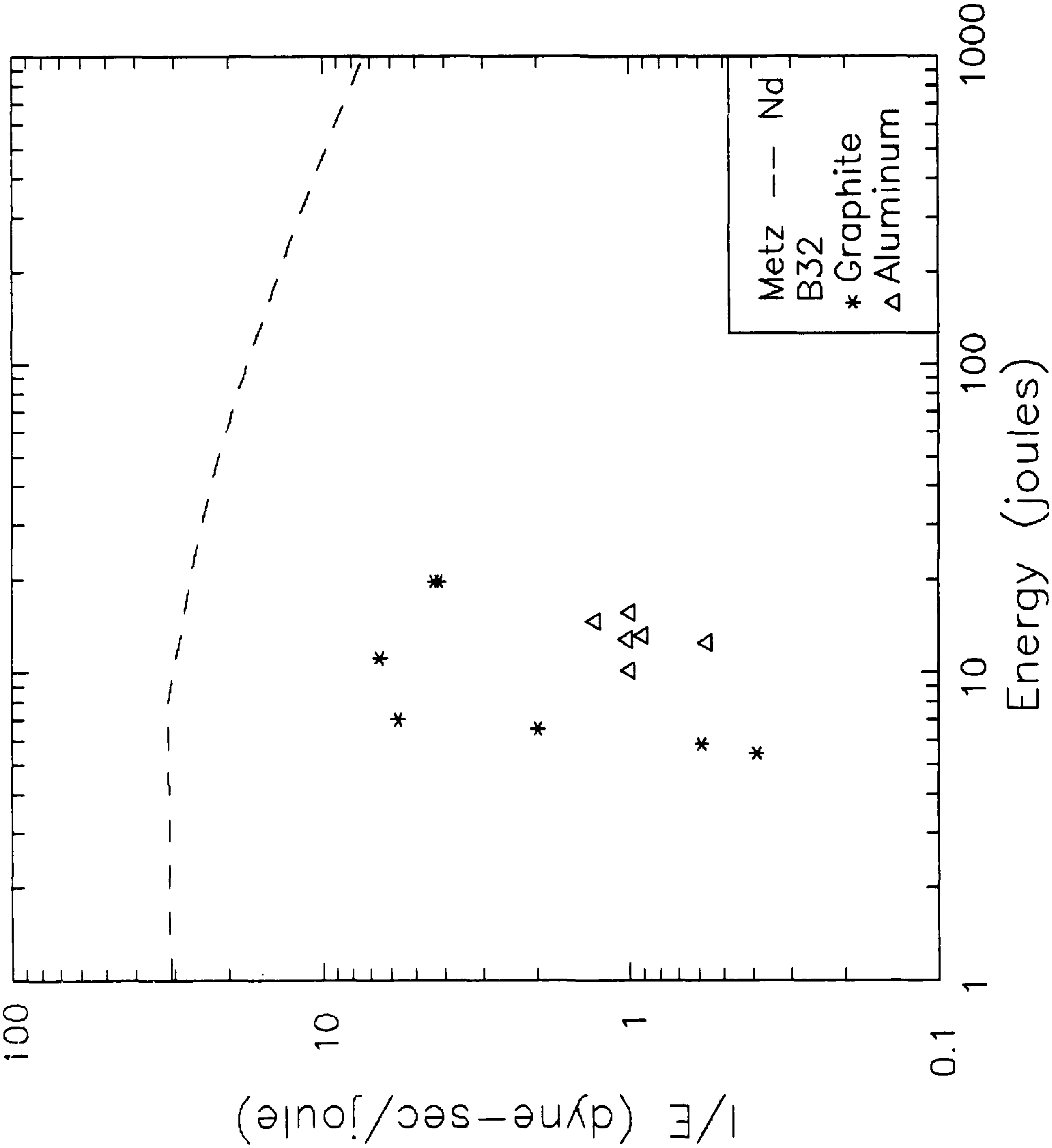
Target dimensions: 4 cm diam (Al), 4 cm square (C)

Measured quantities: total impulse

Measurement technique(s): rotation of potentiometer shaft

Figure caption: Figure 2: Impulse vs. incident energy. Graphite target. 250-psec pulse. Figure 3: Impulse vs. incident energy. Aluminum target. 250-psec pulse.

Comments: The Simons model calculation bears little resemblance to the data. The difference between impulse results in air and in vacuum shows that an air plasma is formed and contributes to the impulse delivery, but is not as effective here as would be a longer laser pulse. Possibly a significant portion of this subnanosecond pulse is spent in energy sinks which are inefficient impulse generators, such as material vaporization and air ionization.


I/E (dyne-sec/joule)
100
10
1
0.1
Energy (joules)
1
10
100
1000
Metz -- Nd
B32
* Graphite
Δ Aluminum

Reference # : B23

Authors : N.N. Kozlova, A.I. Petrukhin, Yu. E. Pleshanov, V.A. Rybakov, and V.A. Sulyaev

Citation: "Measurement of recoil momentum for a laser beam interacting with an absorbing solid surface in air", Fizika Goreniya i Vzryva 11, 650-654 (1975)

Institution:

Experimental Conditions:

Laser: Nd:glass

Wavelength: 1.06 μm

Pulse energy: 30 J

Pulse duration: 0.5 μs fwhm

Intensity range: 20 - 600 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: 0.3, 0.5, 0.8 cm diam

Target materials: aluminum

Target dimensions: 0.5 to 5.0 cm diam

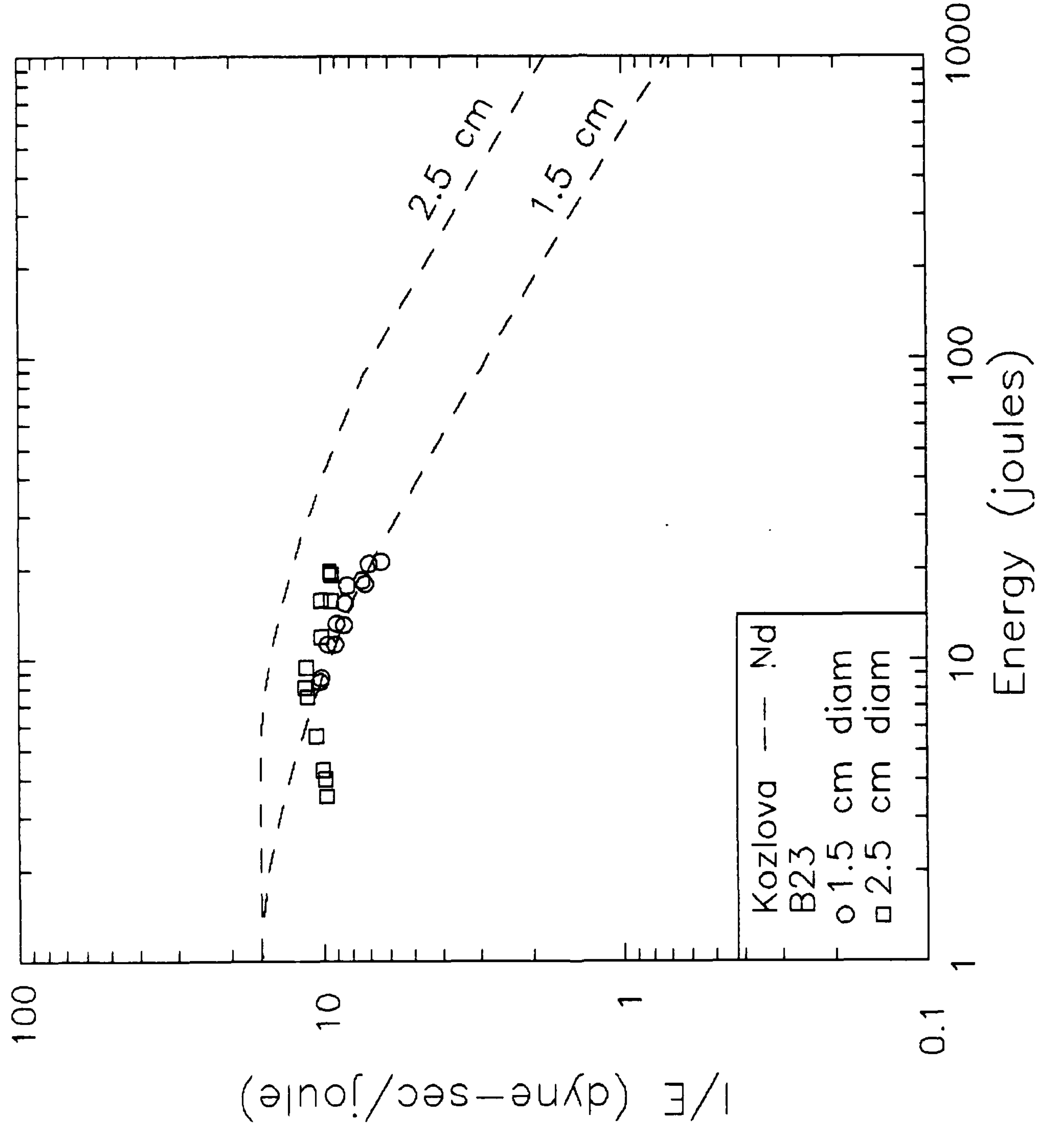
Measured quantities: total impulse

Measurement technique(s): ballistic pendulum. The target disk (pendulum bob) was embedded in a planar sheet with a gap of 0.5 mm between disk and sheet, thus minimizing blast-wave expansion around the edges of the disk.

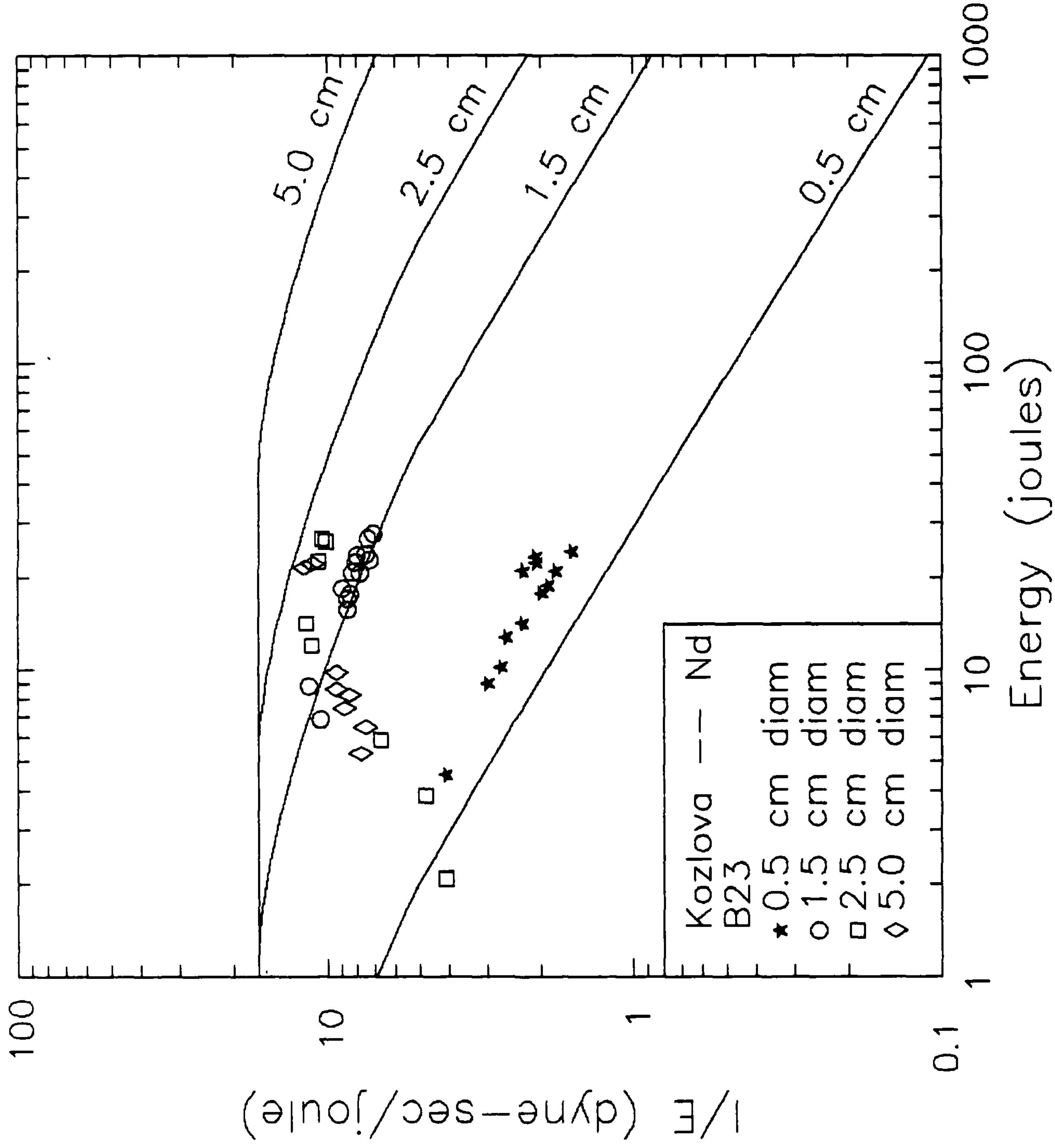
Figure caption: None.

Comments: "The absorbed and theoretical curves show that a laser explosion is similar to a point explosion as regards momentum; the effective energy of the laser explosion is 0.75 of that for the massless explosion (if the comparison is with the calculated curve for the actual equation of state in air)."

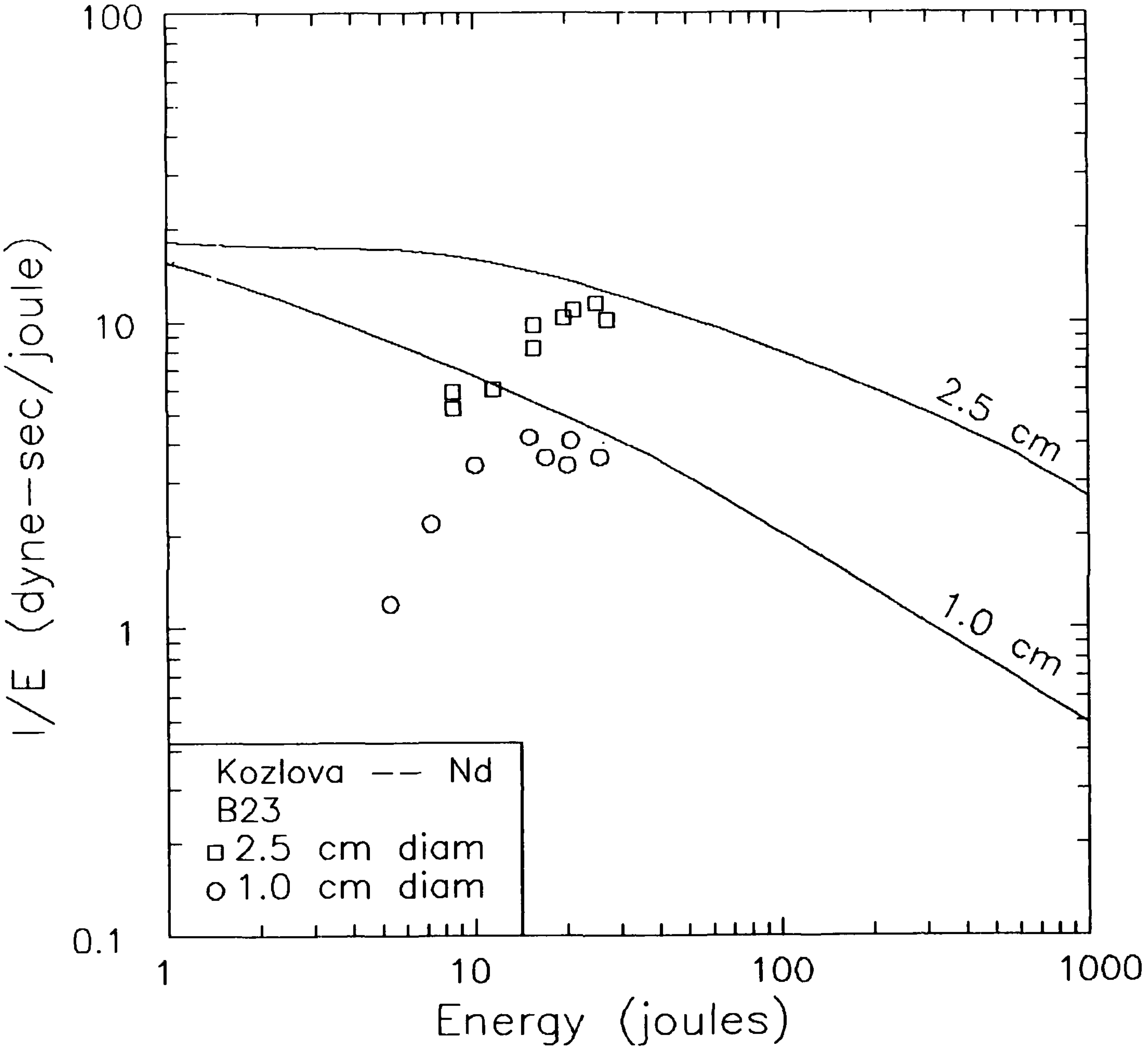
For the 0.8 cm spot diameter, the laser energy is evidently insufficient for the formation of a fully developed air plasma and the impulse delivery is lower than predicted by the Simons model. For the smaller spots, agreement with the model is fairly good, excepting the large-diameter targets, for which the failing validity of simple blast-wave theory in the regime of weak blast pressure causes the model predictions to be higher than observed.



I/E (dyne-sec/joule)
100
10
1
0.1
Energy (joules)
1
10
100
1000
2.5 cm
1.5 cm
Kozlova — Nd
B23
o 1.5 cm diam
□ 2.5 cm diam



I/E (dyne-sec/joule)
100
10
1
0.1
Energy (joules)
1
10
100
1000
5.0 cm
2.5 cm
1.5 cm
0.5 cm
Kozlova — Nd
B23
0.5 cm diam
1.5 cm diam
2.5 cm diam
5.0 cm diam


100
10
1
0.1
1
10
100
1000
I/E (dyne-sec/joule)
Energy (joules)
2.5 cm
1.0 cm
Kozlova -- Nd
B23
□ 2.5 cm diam
○ 1.0 cm diam

Reference # : B33

Authors : L.R. Hettche, T.R. Tucker, J.T. Schriempf, R.L. Stegman, and S.A. Metz

Citation: J. Appl. Phys. 47, 1415-1421 (1976)

Institution: Naval Research Lab

Experimental Conditions:
- Laser: Nd:glass (AFWL, five-stage amplified spontaneous emission type)
  - Wavelength: 1.06 μm
  - Pulse energy: 125 J
  - Pulse duration: 1 μs
- Intensity range: 20 - 600 MW/cm^2
- Atmosphere: 1 atm air

Spot dimensions: 75% of energy in 0.25-cm^2 circle (0.56 cm diam)

Target materials: aluminum (1100), titanium 6Al-4V

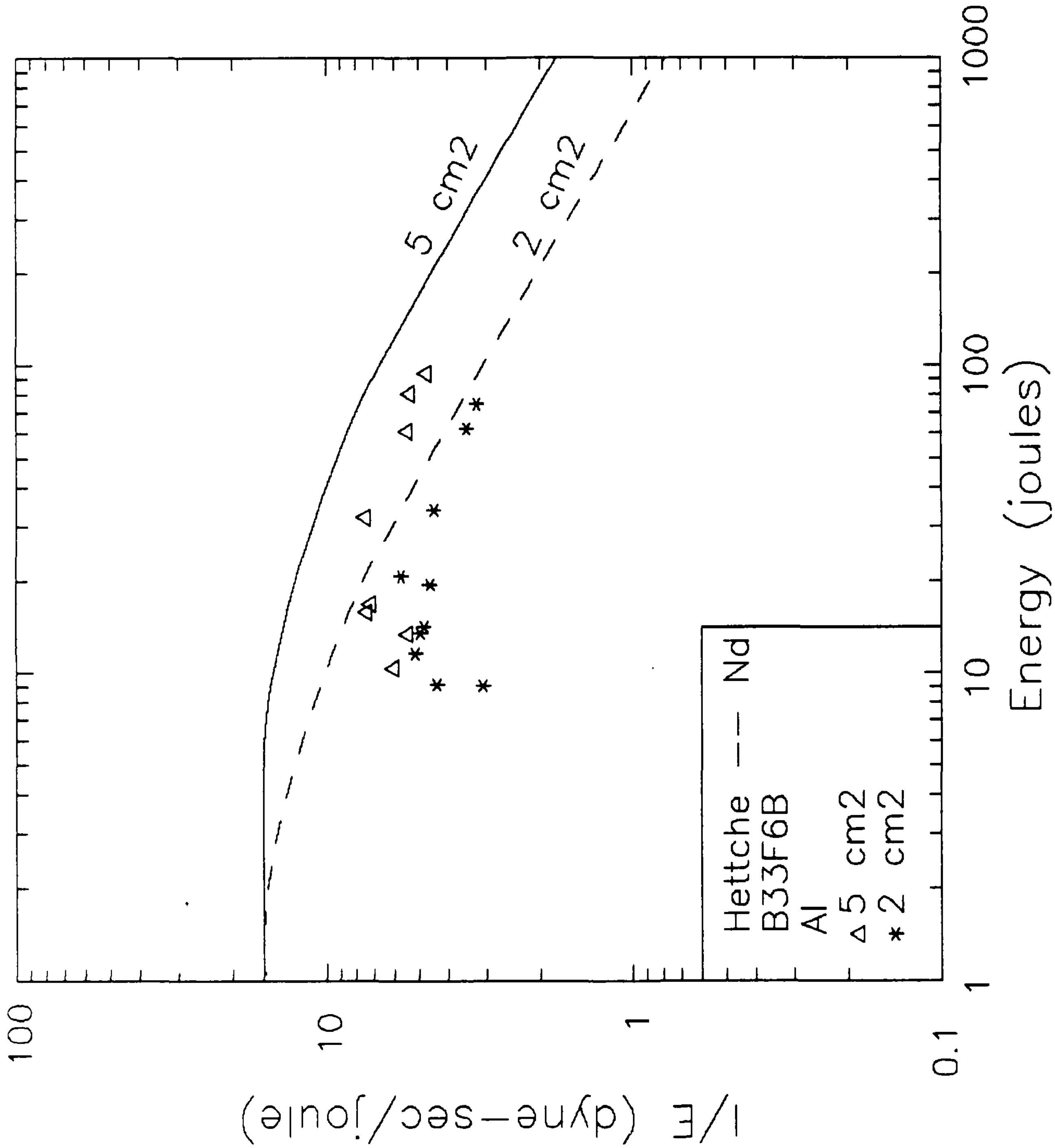
Target dimensions: 1.6, 2.5, 5.0 cm diameter

Measured quantities: pressure, impulse

Measurement technique(s):
- pressure: rear-surface interferometry through quartz rod
- impulse: ballistic pendulum

Figure caption: "Total impulse generated in Al targets is plotted vs. laser energy. . . Increased impulse in the large-diameter specimens indicate[s] that radial plasma expansion plays a role in total impulse generation."

Comments: The pulse durations actually employed for these impulse data are not clear in the report. The authors indicate today that the pulse duration for the impulse work was 1 μs only, and the longer pulses described in the report were used for thermal measurements only.



5 cm2
2 cm2
Hettche — Nd
B33F6B
Al
△ 5 cm2
* 2 cm2
Energy (joules)
I/E (dyne-sec/joule)
1
10
100
1000
0.1
1
10
100

Reference # : T5

Authors: F.W. French, G.W. Zeiders, J.P. Reilly

Citation: "Single pulse laser impulse tests in air with the Battelle 1.06 micron device", WJSA-FR-84-02 (1983)

Institution: W.J. Schafer Associates, Wakefield MA

Experimental Conditions:

Laser: Nd:glass

Wavelength: 1.06 μm

Pulse energy: 200-1000 J

Pulse duration: 40-45 ns

Intensity range: to $2x10^{10}$ W/cm^2

Atmosphere: 1 atm air

Spot dimensions: 0.96, 1.94, and 2.75 cm diam

Target materials: aluminum, carbon (Grafoil)

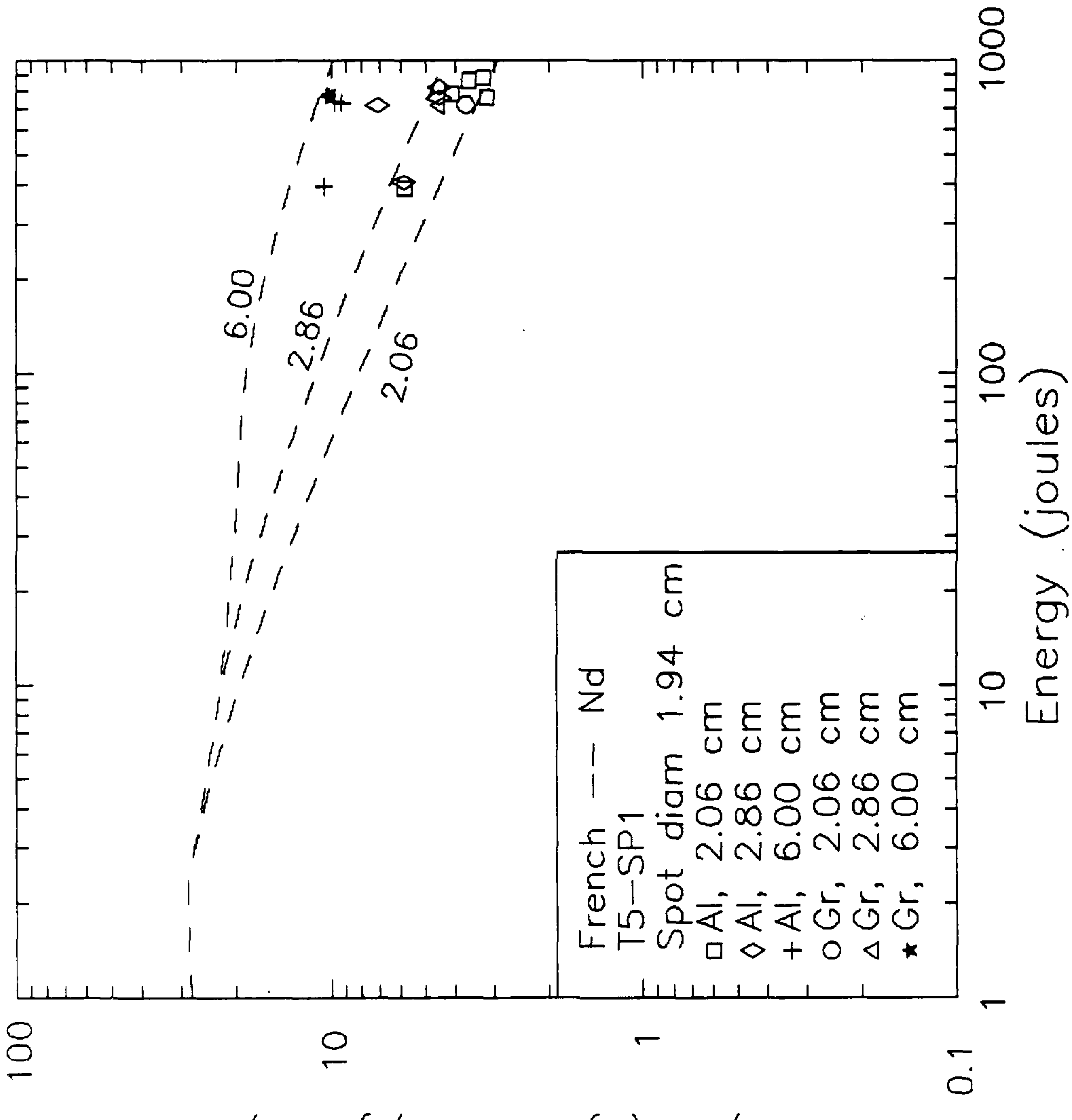
Target dimensions: 2.06, 2.86, and 6.00 cm diam

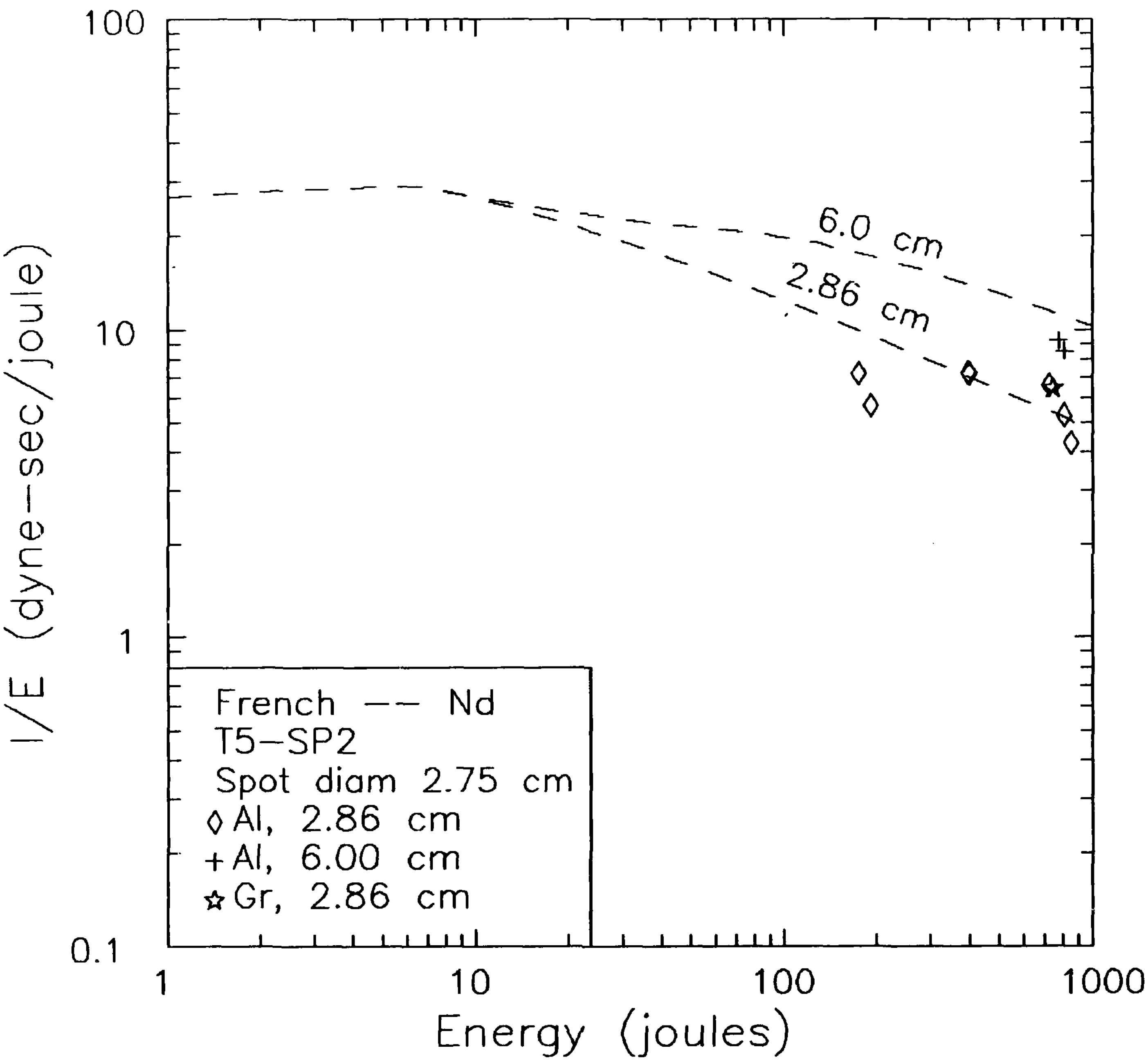
Measured quantities: total impulse

Measurement technique(s): ballistic pendulum

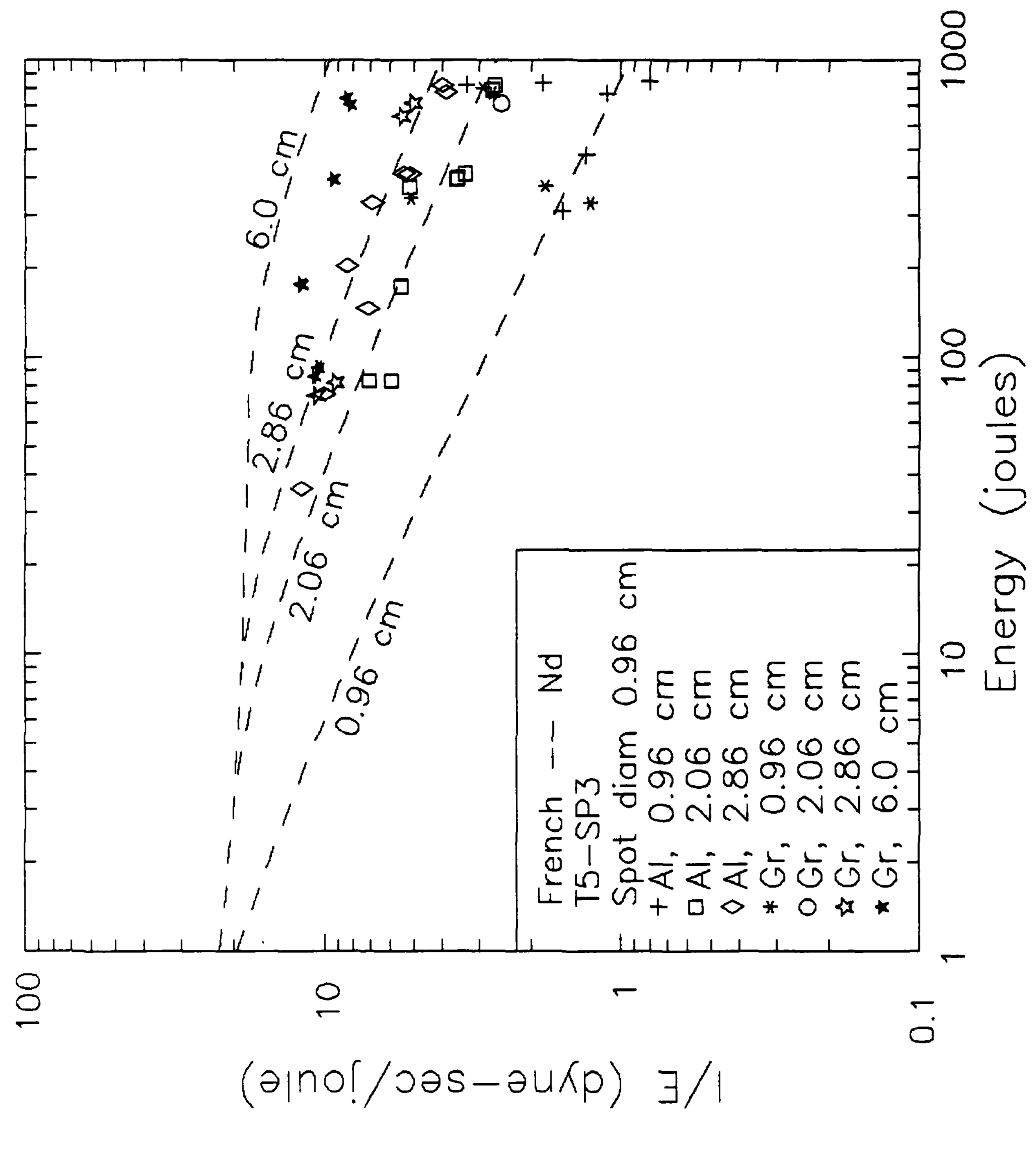
Table caption: "Shot list for laser pendulum impulse experiments at Battelle, April-May 1983."

Comments: These data were taken under conditions of very high laser intensity, as high as can be propagated in air at 1 μm, and low plasma dimensionality. The Simons model for prediction of delivered impulse works well in this regime for targets not very much larger than the laser spot. This particular work is especially valuable for extrapolation to laser lethality conditions, where the intensity must be high in order to deliver lethal impulses in reasonable pulse lengths, and the large spot diameters of realistic conditions implies low plasma dimensionality.


French -- Nd
T5-SP1
Spot diam 1.94 cm
□ Al, 2.06 cm
◇ Al, 2.86 cm
+ Al, 6.00 cm
○ Gr, 2.06 cm
△ Gr, 2.86 cm
★ Gr, 6.00 cm
6.00
2.86
2.06
I/E (dyne-sec/joule)
100
10
1
0.1
1
10
100
1000
Energy (joules)



100
10
1
0.1
I/E (dyne-sec/joule)
1
10
100
1000
Energy (joules)
6.0 cm
2.86 cm
French -- Nd
T5-SP2
Spot diam 2.75 cm
◊ Al, 2.86 cm
+ Al, 6.00 cm
☆ Gr, 2.86 cm


French –– Nd
T5–SP3
Spot diam 0.96 cm
+ Al, 0.96 cm
□ Al, 2.06 cm
◇ Al, 2.86 cm
* Gr, 0.96 cm
○ Gr, 2.06 cm
☆ Gr, 2.86 cm
★ Gr, 6.0 cm
6.0 cm
2.86 cm
2.06 cm
0.96 cm
Energy (joules)
I/E (dyne–sec/joule)
1
10
100
1000
0.1
1
10
100

Reference # : T3

Authors : Bayard S. Holmes

Citation: "Assessment of the vulnerability and lethality of aerospace systems, volume II: laser coupling measurements", Technical Report DNA-TR-85-000, May 1986

Institution: SRI International, Menlo Park CA

Experimental Conditions:
Laser: four-stage Nd:glass (Battelle-Columbus)
Wavelength: 1.06 μm
Pulse energy: to 1 kJ
Pulse duration: 30 ns fwhm
Intensity range: 2×10^{9} - 2×10^{10} W/cm^{2}
Atmosphere: air, 1 atm

Spot dimensions: 1 cm diam

Target materials: aluminum, carbon (Grafoil, rolled graphite)

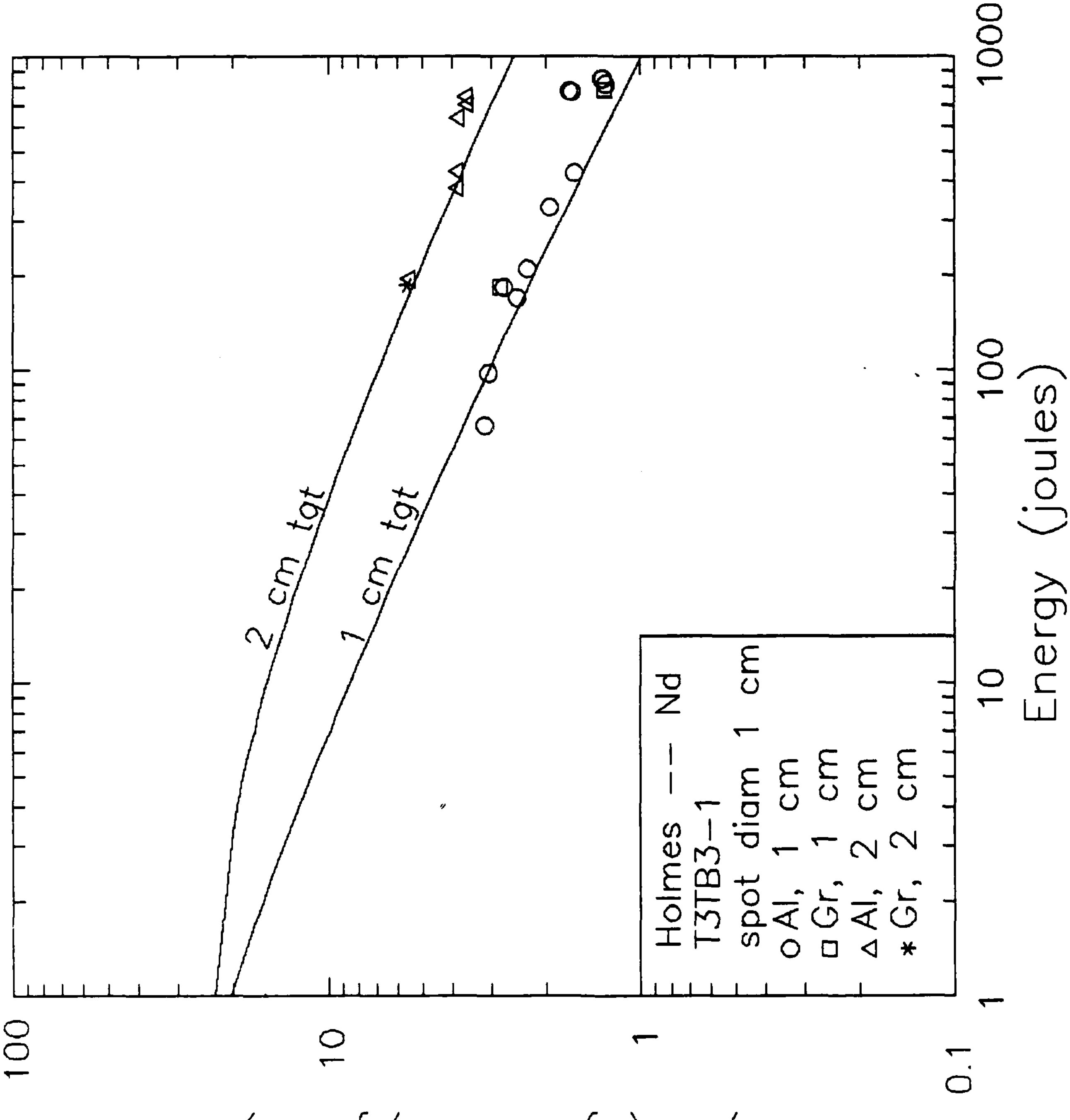
Target dimensions: large compared to laser spot

Measured quantities: total impulse

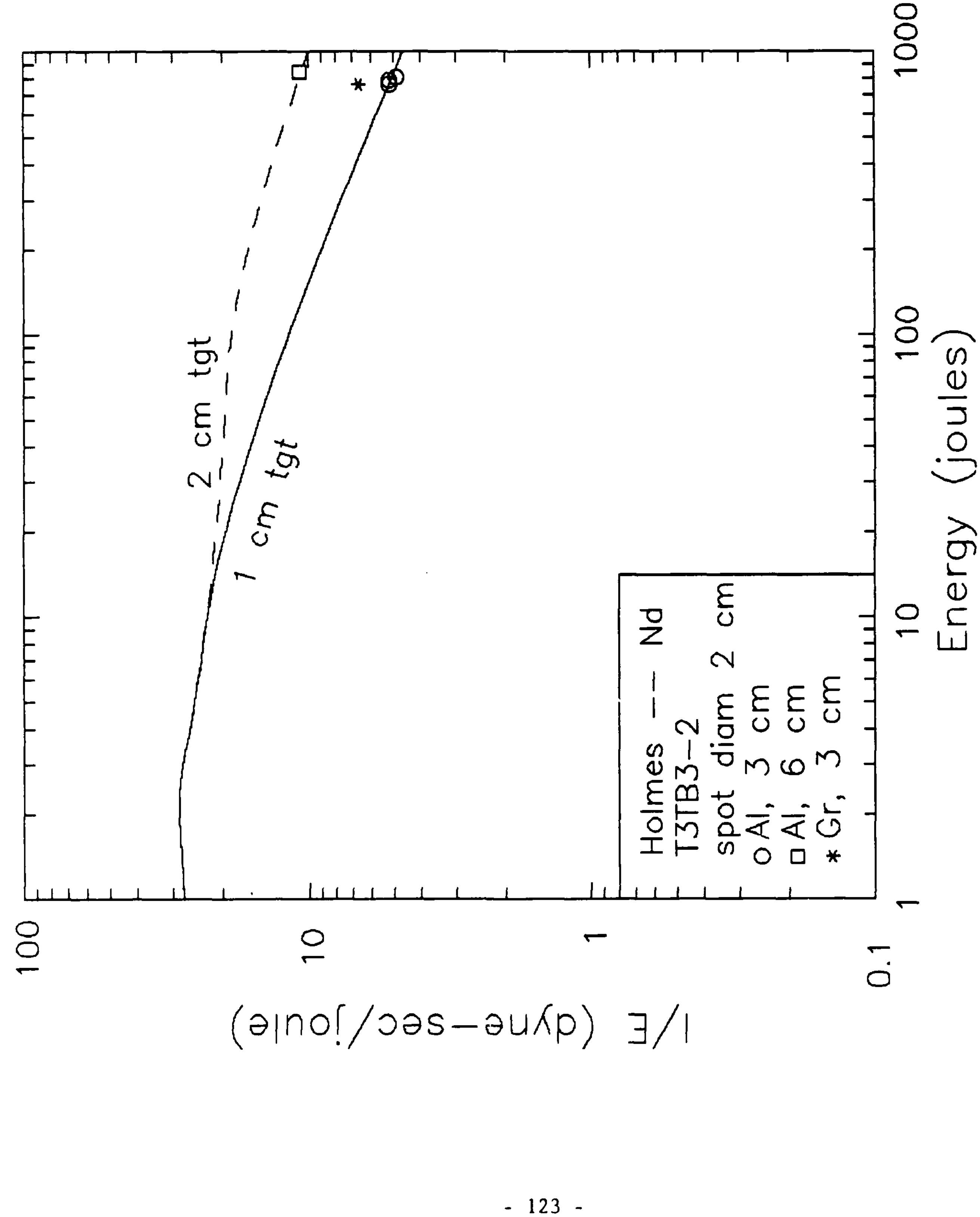
Measurement technique(s): optical velocity transducer behind stress-gauge instrumented target, that mounted on a spring blade or suspended by short strings to permit free motion. This apparatus provides both stress and impulse measurements.

Table caption: "Summary of in-air impulse data obtained at 1 atm ambient pressure."

Comments: In this regime of very high laser intensities, short pulses, relatively large spot diameters (i.e., low dimensionality), and targets not very much larger in diameter than the laser spot, the Simons model accurately predicts the impulse delivery. The transition from an LSD to an absorption wave propagating by ultraviolet-photon emission and absorption has negligible effect on the impulse, despite reducing the peak pressures during the laser pulse.



I/E (dyne–sec/joule)
100
10
1
0.1
Energy (joules)
1
10
100
1000
2 cm tgt
1 cm tgt
Holmes –– Nd
T3TB3–1
spot diam 1 cm
○ Al, 1 cm
□ Gr, 1 cm
△ Al, 2 cm
* Gr, 2 cm



I/E (dyne-sec/joule)
100
10
1
0.1
Energy (joules)
1
10
100
1000
2 cm tgt
1 cm tgt
Holmes --- Nd
T3TB3-2
spot diam 2 cm
○ Al, 3 cm
□ Al, 6 cm
* Gr, 3 cm

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Reference # : B12

Authors : K. Kuriki and Y. Kitora

Citation: "Momentum transfer to target for laser-produced plasma", Appl. Phys. Lett. 30, 443-445 (1977)

Institution: University of Tokyo, Japan

Experimental Conditions:

Laser: Q-switched ruby

Wavelength: 0.69 μm

Pulse energy: 0.3 - 0.8 J

Pulse duration: 30 ns

Intensity range: 1×10^{8} - 3×10^{11} W/cm²

Atmosphere: 1 atm air

Spot dimensions: 0.0 - 0.5 cm diam

Target materials: Gold, nickel, molybdenum

Target dimensions: 5 cm diam

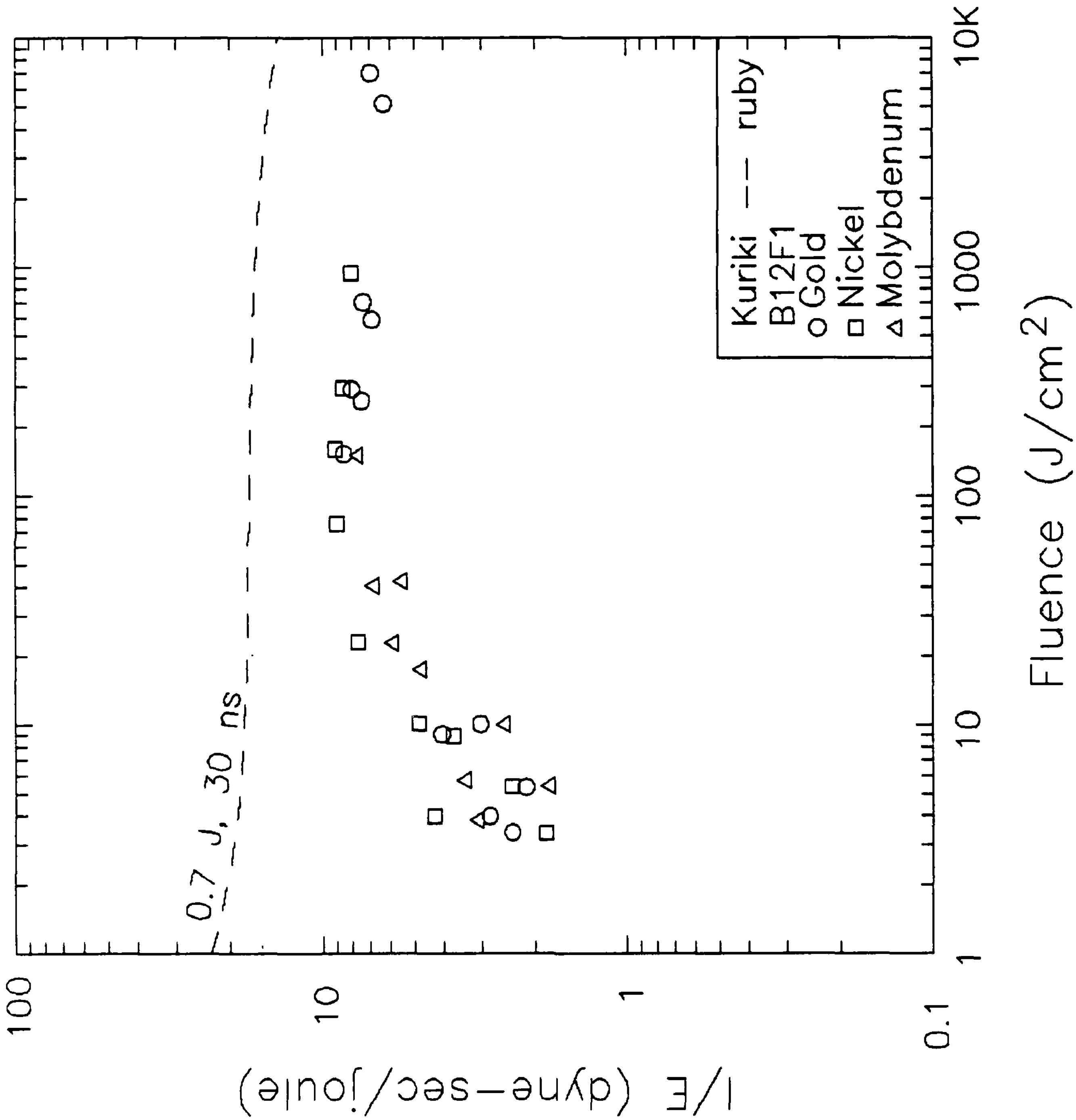
Measured quantities: total impulse

Measurement technique(s): pendulum

Figure caption: "Momentum conversion coefficient for various focal point distances L and target material. E=0.7 J, [pulse duration]=30 nsec, 5-cm lens focal length. Solid line [not reproduced here] represents analytical result."

Comments: The impulse coupling data are given in the original with the spacing from the focusing lens, and the calculated spot diameter, as the independent variable. The diameters were converted to fluence using an energy of 0.7 J. These results, in the mid-visible spectrum, are consistent with those from air plasmas driven by infrared lasers.

These are the highest-intensity data available in air. The ruby laser lies near the peak of the ignition threshold range, the threshold for longer wavelengths being lower due to inverse bremsstrahlung absorption, while the thresholds for shorter wavelengths are lower due to multiphoton absorption.


Kuriki — ruby
B12F1
○ Gold
□ Nickel
△ Molybdenum
0.7 J, 30 ns
Fluence (J/cm^2)
I/E (dyne−sec/joule)
1
10
100
1000
10K
0.1
1
10
100

Reference # : B38

Authors : J.A. Woodroffe, C. Duzy, J. Hsia, and A. Ballantyne

Citation: "UV/Visible laser effects", Laser Vulnerability, Effects, and Hardening, p. 263-266 (1980).

Institution: Avco-Everett Research Laboratory, Everett MA

Experimental Conditions:

Laser: electron-beam-pumped XeF

Wavelength: 0.35 μm

Pulse energy: 1.4 J maximum

Pulse duration: 0.6 μs

Intensity range: 20 - 60 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: variable, 0.04 to 0.1 cm^2

Target materials: aluminum (2024-T3)

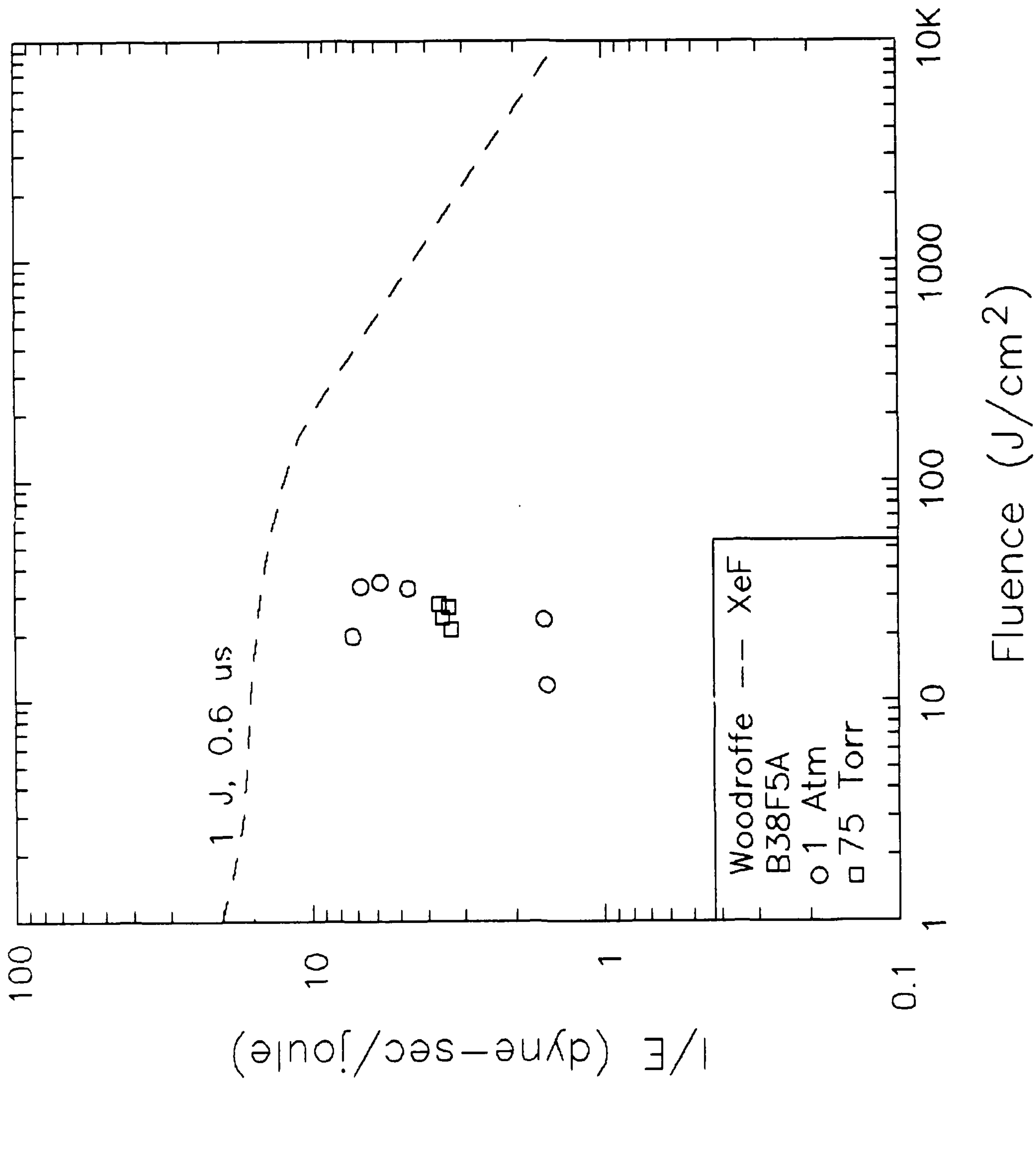
Target dimensions: not stated

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Impulse coupling coefficient for XeF to an aluminum surface as a function of incident fluence. Energies of 0.8-1.4 joules were used."

Comments: The impulse observed here is believed to be due to surface ablation, with air dynamics playing no significant role. Similar measurements under reduced atmospheric pressure (0.1 atm) show no change in impulse coupling. A "surface flash" was evident, but apparently not an indication of the formation of an opaque LSD.



I/E (dyne-sec/joule)
100
10
1
0.1
1
10
100
1000
10K
Fluence (J/cm2)
1 J, 0.6 us
Woodroffe -- XeF
B38F5A
o 1 Atm
□ 75 Torr

Reference # : B38

Authors : J.A. Woodroffe, C. Duzy, J. Hsia, and A. Ballantyne

Citation: "UV/Visible laser effects", Laser Vulnerability, Effects, and Hardening, p. 263-266 (1980). The KrF portion is reported also in "Thermal and impulse coupling to an aluminum surface by a pulsed KrF laser", Appl. Phys. Lett. 36, 14-15 (1980);

Institution: Avco-Everett Research Laboratory, Everett MA

Experimental Conditions:

Laser: electron-beam-pumped KrF

Wavelength: 0.25 μm

Pulse energy: 20 J

Pulse duration: 0.5 μs

Intensity range: 10 - 100 MW/cm^2

Atmosphere: 1 atm air

Spot dimensions: variable, 0.04 to 0.6 cm^2

Target materials: aluminum (2024-T3)

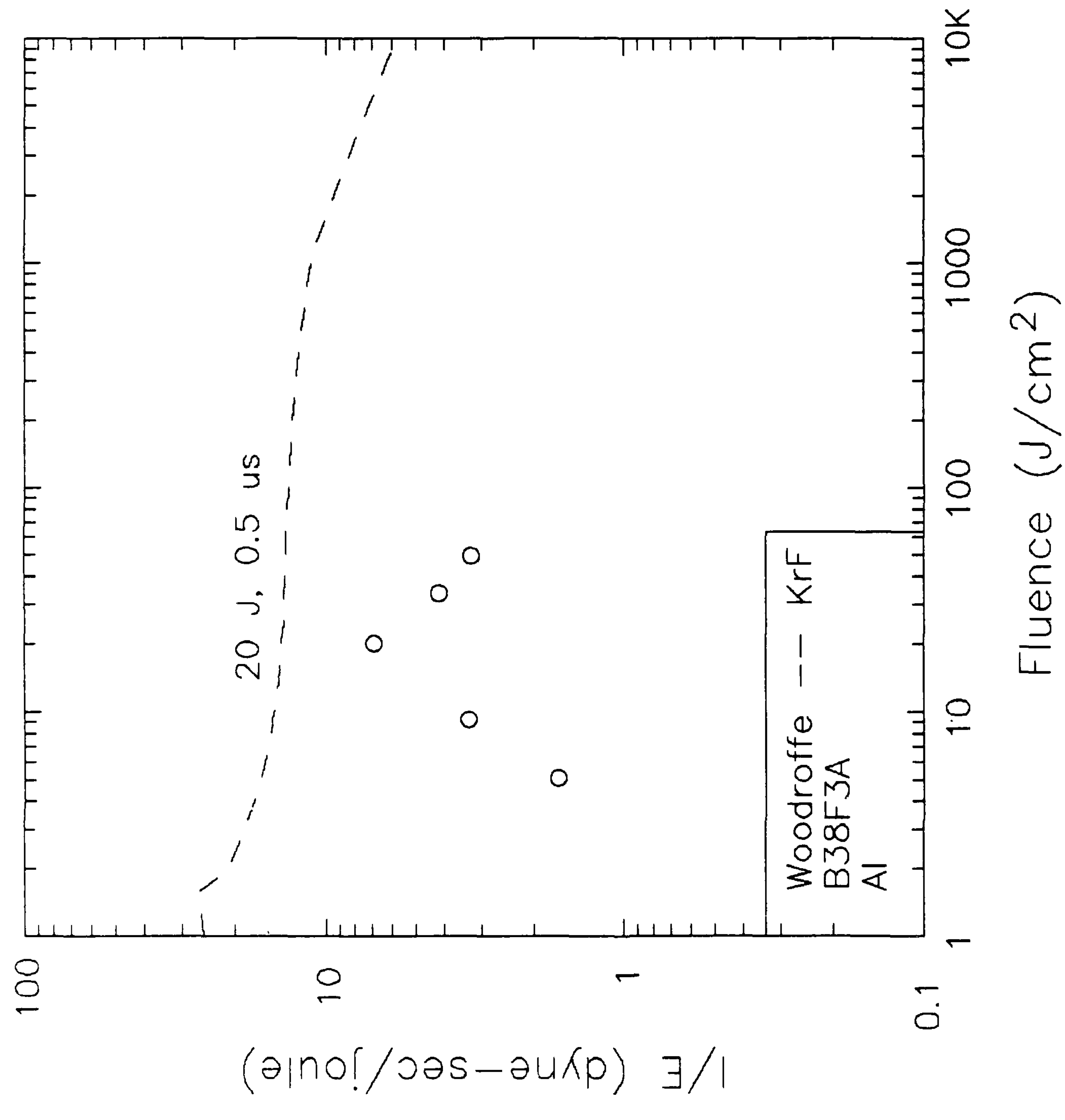
Target dimensions: not stated

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Impulse produced by a KrF laser pulse on aluminum. Pressure: 1 atmosphere, pulse energy: 20 joules, pulse length: 0.5 μsec. . . The light liness [not reproduced here] are calculations for plasma (laser supported detonation wave) impulse with an ignition threshold of 3 J/cm^2 and vapor induced impulse with 40% inherent absorptivity."

Comments: A rise in coupling associated with ignition threshold is evident. The coupling decreases beyond about 20 J/cm^2 fluence, a decline attributed by the authors to the usual decrease with increasing flux of LSD-generated impulse. The Simons theory predicts, however, a more modest rate of decrease.



I/E (dyne-sec/joule)
100
10
1
0.1
1
10
100
1000
10K
Fluence (J/cm^2)
20 J, 0.5 us
Woodroffe -- KrF
B38F3A
Al

IMPULSE MEASUREMENTS VS. AIR PRESSURE/DENSITY

#	1st au	yr	wavel	matls
B2	Shui	1978	10.6	Aluminum, 2024 alloy, bare and painted; carbon phenolic; carbon cloth

IMPULSE DATA AT REDUCED AIR DENSITY

As mentioned in another section, only a few works have been found providing laser-plasma-generated pressure data as a function of ambient air density (pressure). The shortage of works on impulse at reduced air density is even more striking: only one has been found, and that one falls short of covering the range from vacuum to one atmosphere.

Specific impulse is expected to decrease with decreasing air density, a result of some significance for effects on objects at even moderate altitudes. The total impulse is expected to behave in a rather complex way, depending on the pulse duration and the dimensions of the laser spot and target. At some very uncertain air density, wavelength-dependent and possibly intensity-dependent, the air plasma will fail and be replaced by a vacuum-type plasma (if the laser intensity is sufficient) or no significant impulse interaction at all (if the laser intensity is above threshold for plasma ignition in air but below threshold for plasma ignition in vacuum).

The behavior of impulse coupling with ambient air density, including the coupling coefficient, the spatial distribution, and the transition to vacuum coupling, is a major unknown. The single set of data available sheds little light on the problem.

Reference # : B2

Authors : Ven H. Shui, Lee A. Young, and James P. Reilly

Citation: "Impulse transfer from pulsed CO_2 laser irradiation at reduced ambient pressures", AIAA Journal 16, 649-650 (1978)

Institution: Avco Everett Research Laboratory, Everett MA

Experimental Conditions:
- Laser: TEA CO_2
  - Wavelength: 10.6 μm
  - Pulse energy: 110-270 J
  - Pulse duration: nominally 10 μs; 80% of energy in first 8-14 μs, remainder in 5-15 μs
- Intensity range: 6 - 240 MW/cm^2
- Atmosphere: 0.01 - 10 Torr

Spot dimensions: 0.38 - 2.3 cm diameter

Target materials: Aluminum, 2024 alloy, bare and painted; carbon phenolic; carbon cloth

Target dimensions: 31 cm diameter

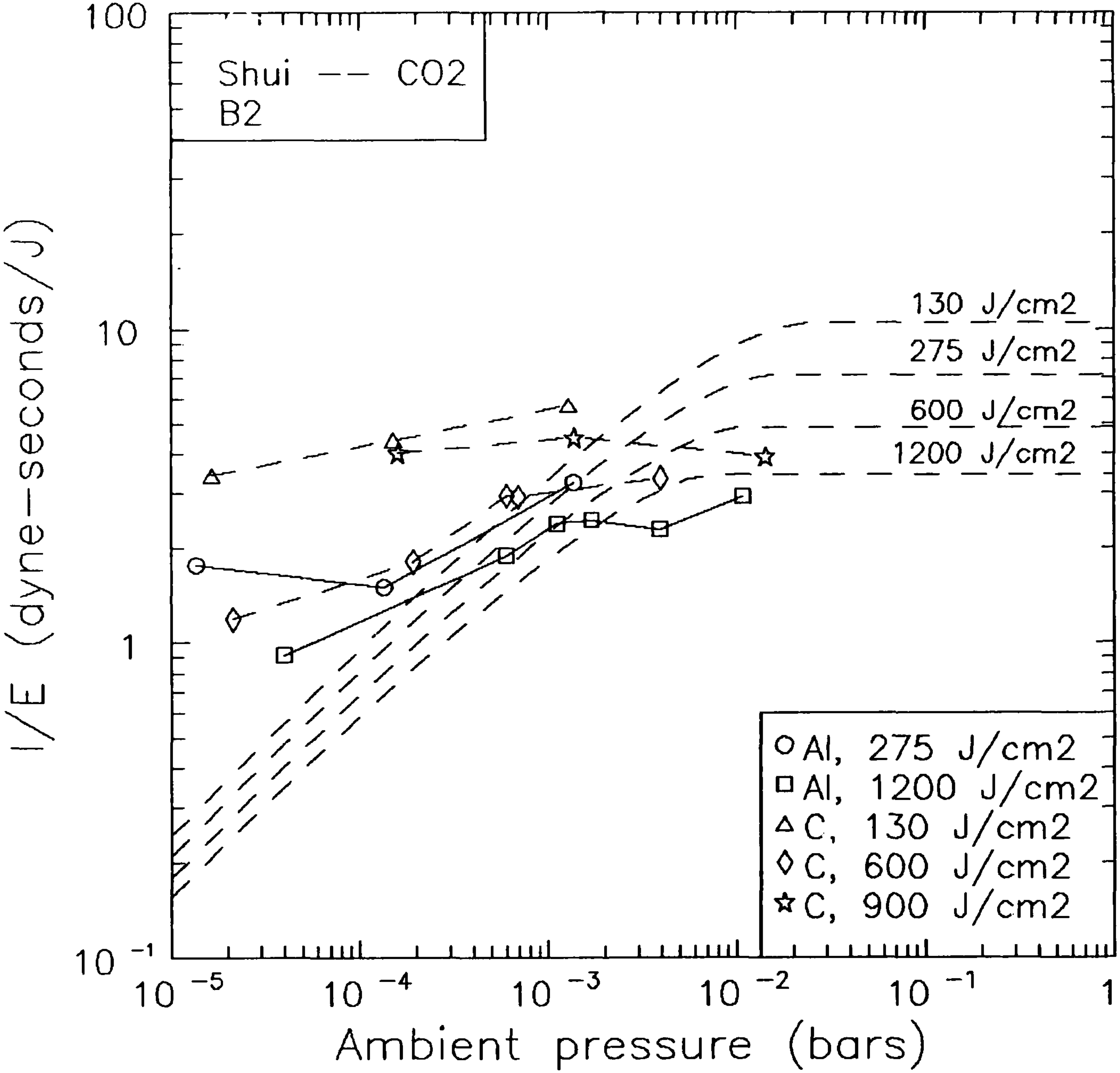
Measured quantities: total impulse

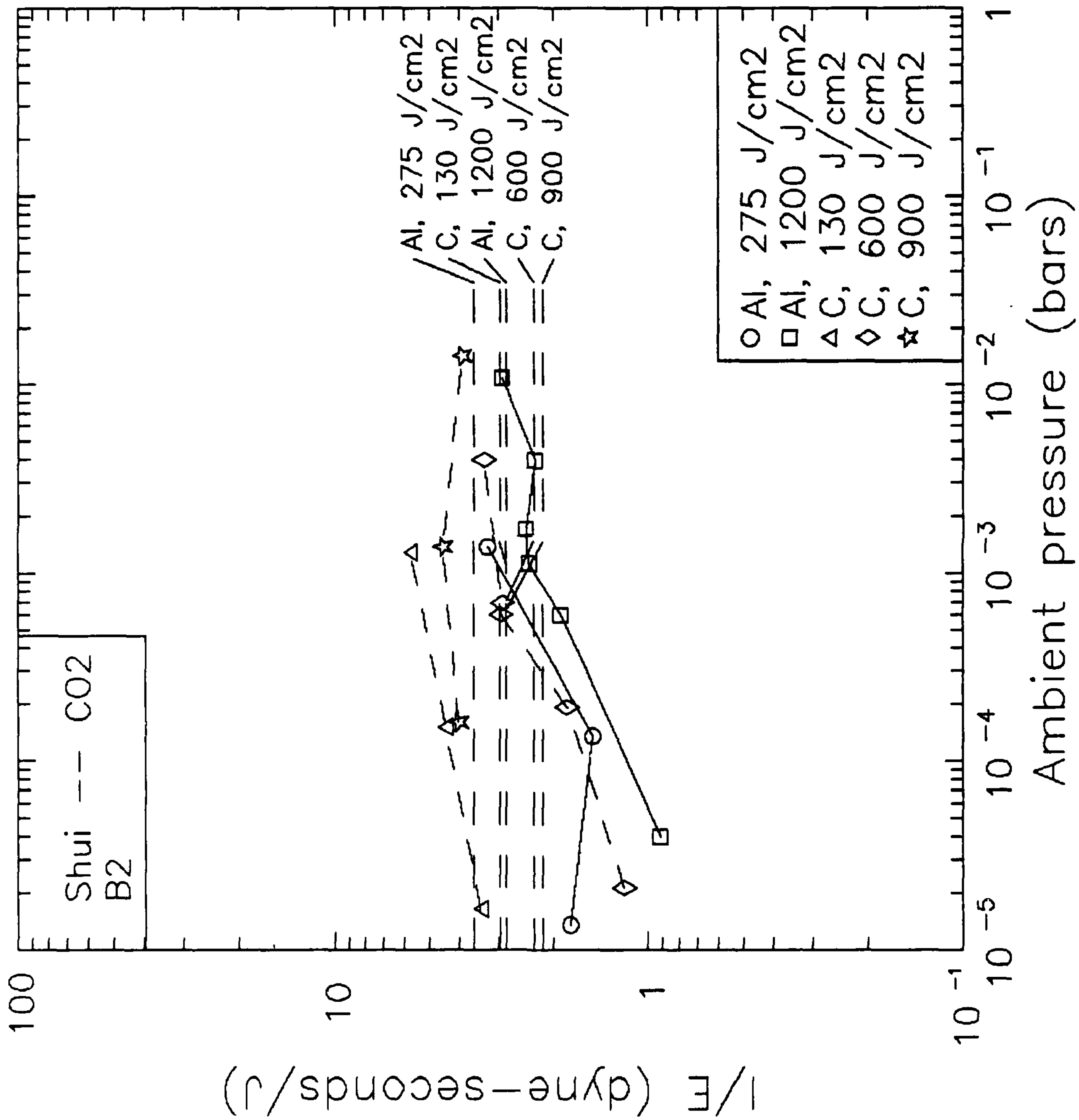
Measurement technique: ballistic pendulum

Figure caption: "Impulse per incident energy (impulse/energy coupling coefficient) as a function of ambient pressure."

Comments: The observed impulse values are practically independent of ambient pressure over this range. The maximum ambient pressure, 10 Torr (0.013 bar), is below the air plasma - vacuum interaction transition evident from measurements of peak pressure versus ambient pressure (papers B13, B17). The first figure here shows the data compared to air-plasma curves calculated using the Simons model. The second shows the same data compared to the coupling values predicted by the Pirri vacuum-ablation model (the values independent, of course, of ambient pressure). It appears that the interaction here is primarily one of target ablation, rather than air-plasma blast-wave expansion. The variation on carbon phenolic between 130 and 900 J/cm^2 is not explicable.

"The increase in [impulse coupling coefficient] with ambient pressure exhibited by the experimental data plotted in Fig. 2 is consistent with the theoretical consideration that impulse from expansion increases with ambient pressure."


Shui -- CO2
B2
130 J/cm2
275 J/cm2
600 J/cm2
1200 J/cm2
Al, 275 J/cm2
Al, 1200 J/cm2
C, 130 J/cm2
C, 600 J/cm2
C, 900 J/cm2
I/E (dyne-seconds/J)
100
10
1
10^{-1}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Ambient pressure (bars)


Shui --- CO2
B2
Al, 275 J/cm2
C, 130 J/cm2
Al, 1200 J/cm2
C, 600 J/cm2
C, 900 J/cm2
Al, 275 J/cm2
Al, 1200 J/cm2
C, 130 J/cm2
C, 600 J/cm2
C, 900 J/cm2
I/E (dyne-seconds/J)
Ambient pressure (bars)
100
10
1
10^-1
10^-5
10^-4
10^-3
10^-2
10^-1
1

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IMPULSE DATA IN VACUUM

#	1st author	yr	wavel	matls
CO_2:				
B3	Apostol	1976	10.6	Bismuth, lead, zinc, aluminum
A04	Rosen	1978	10.6	Carbon phenolic, asbestos phenolic, silica phenolic, carbon-carbon, Teflon, ATJ-S graphite, aluminum foil on carbon phenolic, copper sheet on carbon phenolic, gold electroplated on graphite
B2	Shui	1978	10.6	Aluminum, 2024 alloy, bare and painted; carbon phenolic, carbon cloth
B30	Ursu	1981	10.6	Stainless steel
GEM1	Phipps	1984	10.6	Aluminum, titanium, Kevlar epoxy, carbon phenolic, Vamac, Lucite, "LRN"
GEM2	Phipps	1984	10.6	Titanium, "other materials"
HF/DF:				
MJOL	Phipps	1984	2.7-3.2	Aluminum, titanium, Kevlar epoxy, carbon phenolic, Vamac, TBR, HARF 3, HARF 7
Nd:				
B4	Rudder	--	1.06	Titanium 6Al-4V
B32	Metz	1973	1.06	Aluminum, carbon (POCO AXF-5Q graphite)
B40	Rudder	1974	1.06	2024-T3 Al, Grafoil, titanium 6Al-4V
B26	Zweigenbaum	1977	1.06	Aluminum foils
B25	Arad	1979	1.06	Aluminum foils
B6	Askar'yan	1981	1.06	Steel
GRUN	Grun	1981	1.06	Polystyrene
MEYER1	Meyer	1984	1.06	Aluminum foil
ROSEN	Rollins	1985	1.05	Aluminum, S-glass epoxy

Ruby:				
B8	Gregg	1966	0.69	Beryllium, graphite, aluminum, zinc, silver, tungsten
XeF:				
B38F4	Duzy	1980	0.35	2024-T3 aluminum
A07	Rosen	1982	0.35	Titanium 6Al-4V alloy
B11	Rosen	1982	0.35	2024 aluminum alloy
MEYER1	Meyer	1984	0.35	Aluminum foil
T1	Wilson	1986	0.35	Aluminum
T2TB1V	Wilson	1986	0.35	Aluminum, Chemglaze, S-glass epoxy
T6	Augustoni	1986	0.35	Aluminum, S-glass epoxy
VERAC	Ermer	1987	0.35	Aluminum, 2026, 6061, and 1100 alloys; S-glass epoxy
KrF:				
Sprite I	Dingus	1985	0.25	Aluminum, titanium, TBR (titanium-bearing resin), graphite epoxy, carbon phenolic, Kevlar epoxy, silica phenolic, Vamac, Lucite
Sprite II	Dingus	1985	0.25	Aluminum
WILSON	Wilson	1987	0.25	Aluminum

IMPULSE DATA IN VACUUM

The following figures show the data available for impulse delivery in vacuum. The data are shown versus laser irradiance, the predominant independent variable for impulse coupling in vacuum. The range of irradiance is from 1×10^6 W/cm^2 -- below which no significant impulse is detected -- to 1×10^{14} W/cm^2 -- about the maximum achievable with millimeter spot dimensions and nanosecond lasers. This covers the range of irradiances of interest for damage effects.

Shown on each plot is the impulse coupling predicted by the simple Pirri model [1], an extension of the Basov steady-state-ablation model [2]. Pirri's analysis yields, for the impulse coupling coefficient I/E,

$$I/E = 0.0425 \; [\; M^{7/2} \, c^2 \, / \, \phi^2 \, r_s \, l^2 \;]^{1/9} \;,$$

in dyne-seconds/joule. Here

M = atomic weight of the target material, amu
c = speed of light,
l = laser wavelength, in units consistent with c,
r_s = spot radius, cm, and
ϕ = laser irradiance, W/cm^2.

The principal feature of this expression is the $\phi^{-2/9}$ dependence on irradiance. The pulse duration does not enter into the calculation since the model supposes the achievement of a dynamic equilibrium condition.

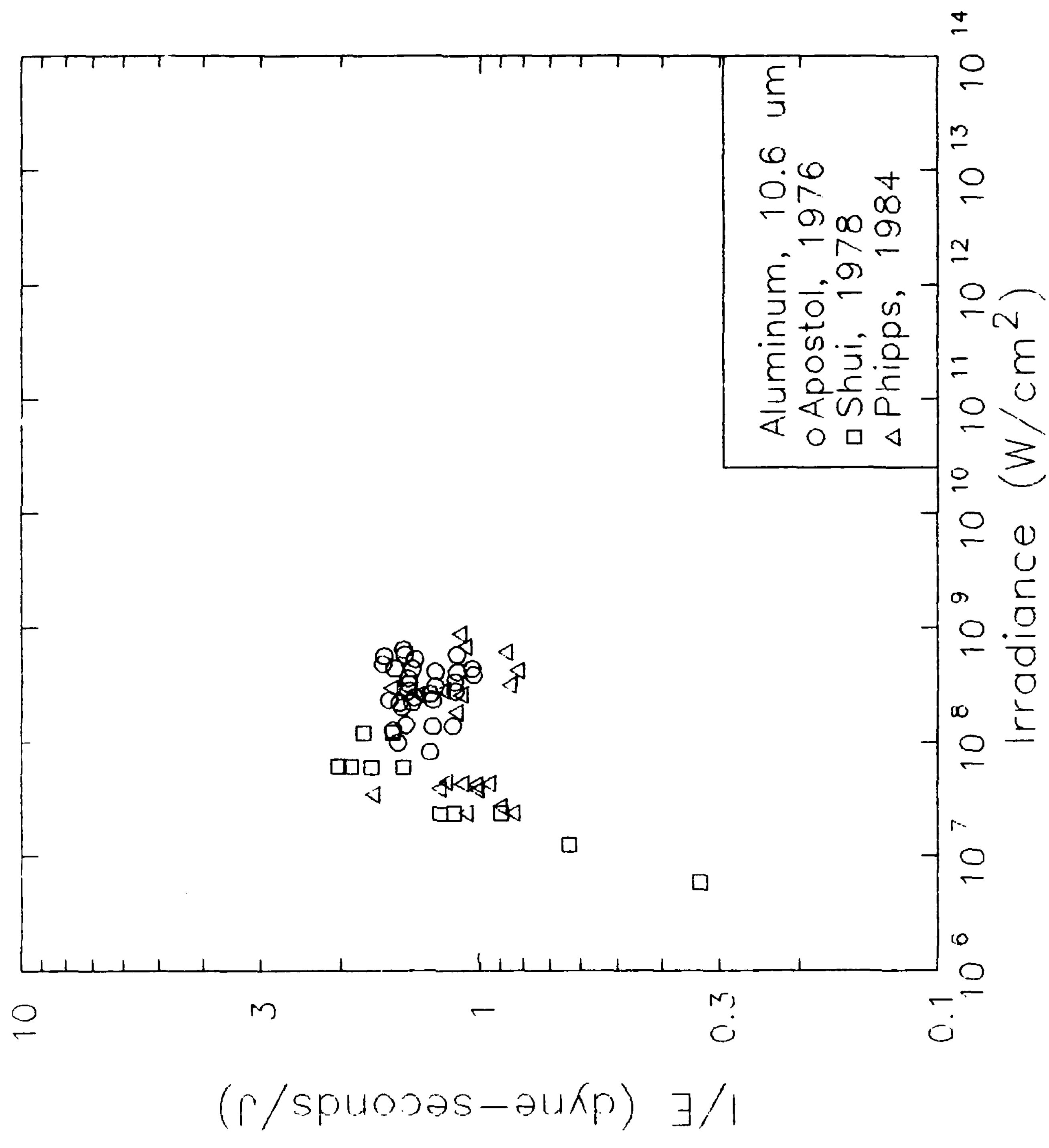
The Pirri model is by no means supposed to compete with sophisticated computer-code models, but is included as a general "reference" against which to compare the data. In two regimes it is not expected to be valid, even approximately: near ignition, where the energy lost to material vaporization is significant, and for large spots and short pulse durations, where a radial equilibrium flow of vaporized material cannot be set up. Nevertheless, as a cursory examination of the data plots will show, the model yields an excellent indication of the order of magnitude and general trends of the data over a remarkable range of laser irradiances and irradiance conditions.

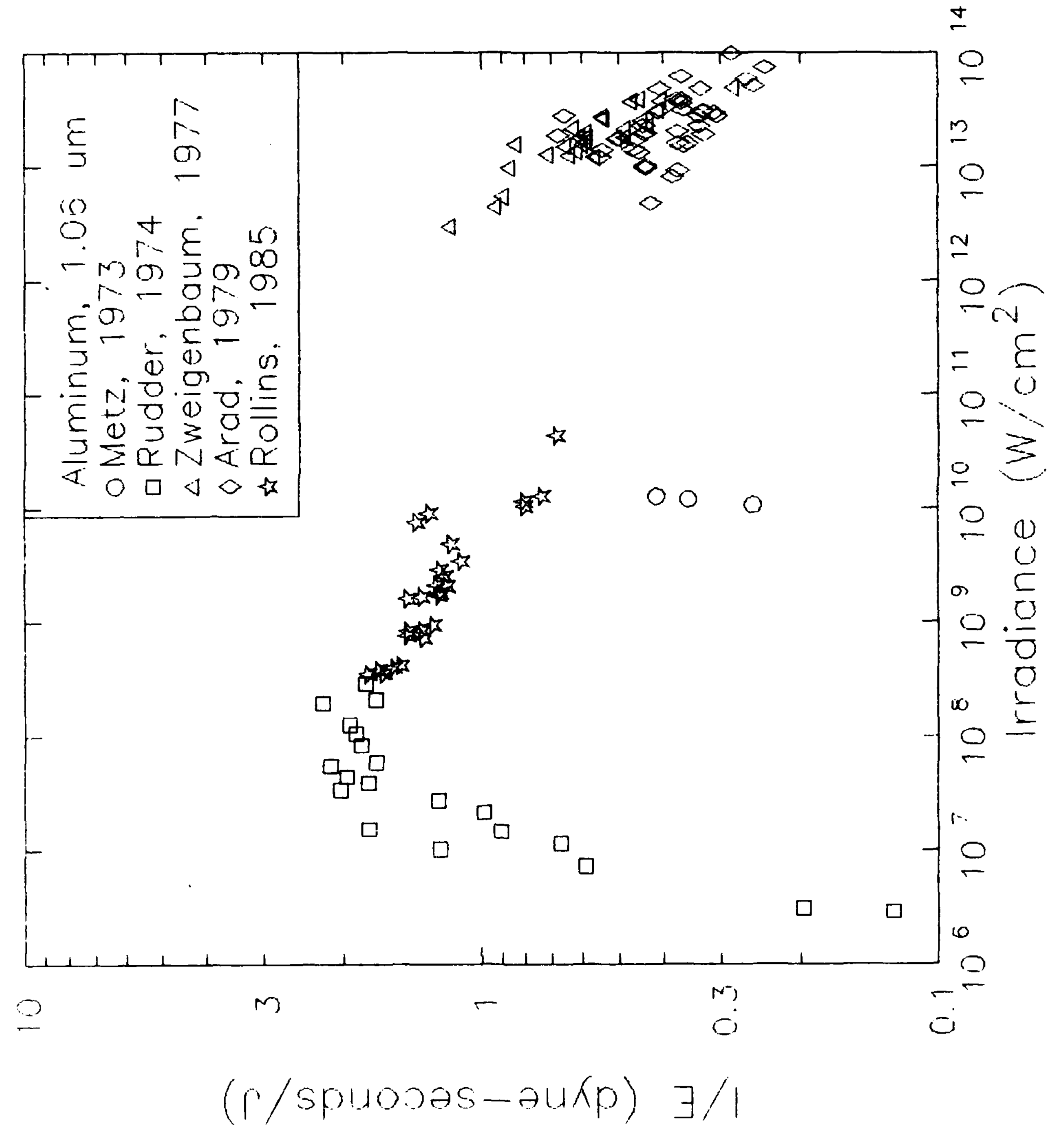
The data have been separated by laser wavelength, from CO_2 (10.6 μm) to KrF (0.25 μm). No data for wavelengths outside this range have been found. Aluminum is the single material most commonly studied, and each laser section is introduced with a chart displaying all the data available at that wavelength on aluminum. Clearly this is comparing "apples and oranges", since the experimental data may differ substantially in pulse duration (which should not matter) and spot radius (which should matter). These charts are included to display the range of irradiances studied at each wavelength, and to illustrate the overall trends of the data at that wavelength. These charts reveal, for example, a surprising gap in the coverage at 1.06 μm, and the shortage of high-irradiance data at 0.35 μm, gaps which might be indications for additional work. The XeF chart also shows a remarkable variation in the values of I/E at all irradiance levels. The low-irradiance data from Maxwell Laboratories have long been a matter of concern, being substantially higher than other impulse data at the XeF wavelength. The high-irradiance 0.35 μm data are from tripled

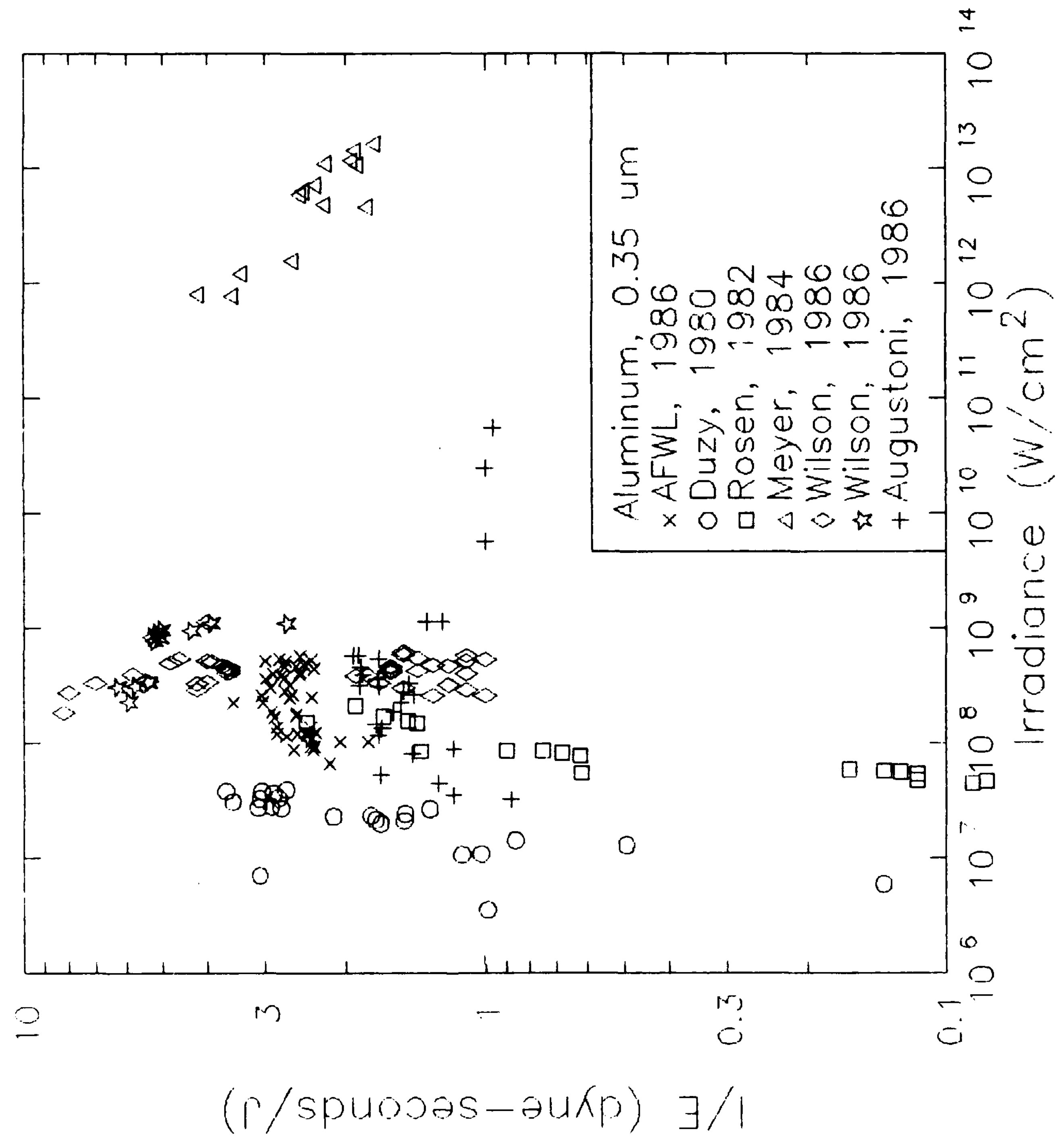
neodymium-glass, and also lie much higher than one would expect, either by comparison with other data or by comparison with the Pirri model prediction.

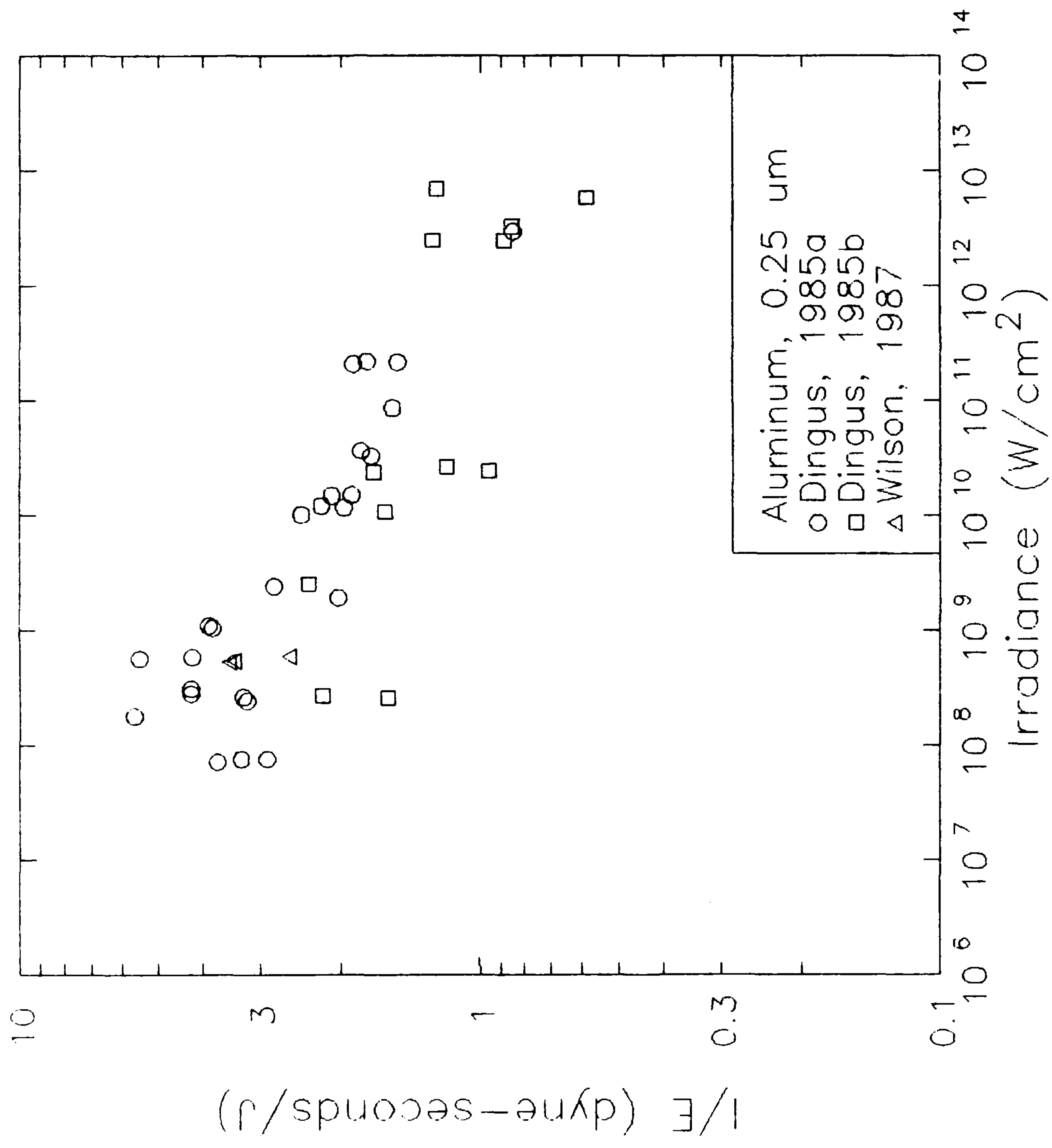
[1] Anthony N. Pirri, "Theory for laser simulation of hypervelocity impact", Phys. Fluids 20, 221-228 (1977).

[2] N.G. Basov, V.A. Gribkov, O.N. Krokhin, and G.V. Sklizkov, "High temperature effects of intense laser emission focused on a solid target", Sov. Phys. JETP 27, 575-582 (1968).


Aluminum, 10.6 um
Apostol, 1976
Shui, 1978
Phipps, 1984
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm^2)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}


Aluminum, 1.06 um
Metz, 1973
Rudder, 1974
Zweigenbaum, 1977
Arad, 1979
Rollins, 1985
I/E (dyne-seconds/J)
Irradiance (W/cm2)


Aluminum, 0.35 um
× AFWL, 1986
○ Duzy, 1980
□ Rosen, 1982
△ Meyer, 1984
◇ Wilson, 1986
☆ Wilson, 1986
+ Augustoni, 1986
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}


Aluminum, 0.25 um
○ Dingus, 1985a
□ Dingus, 1985b
△ Wilson, 1987
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

Reference # : B3

Authors : I. Apostol, V.A. Vatanov, I.N. Mikheilesku, I. Morzhan, A.M. Prokhorov, and V.B. Fedorov

Citation: "Recoil impulse received by metal targets as a result of interaction with microsecond CO_2 laser radiation", Sov. J. Quantum Electron. 6, 1119-1120 (1976)

Institution: Lebedev Physics Institute, Moscow USSR

Experimental Conditions:

Laser: TEA CO_2

Wavelength: 10.6 μm

Pulse energy: Not explicitly stated; about 3 J

Pulse duration: 150 ns spike plus 2.5 μs tail

Intensity range: 1×10^7 - 6×10^8 W/cm^2 (tail)

Atmosphere: vacuum, 0.001-0.01 Torr (1-13 μbar)

Spot dimensions: 0.05 cm diameter

Target material: Bismuth, lead, zinc, aluminum (pure, single crystals)

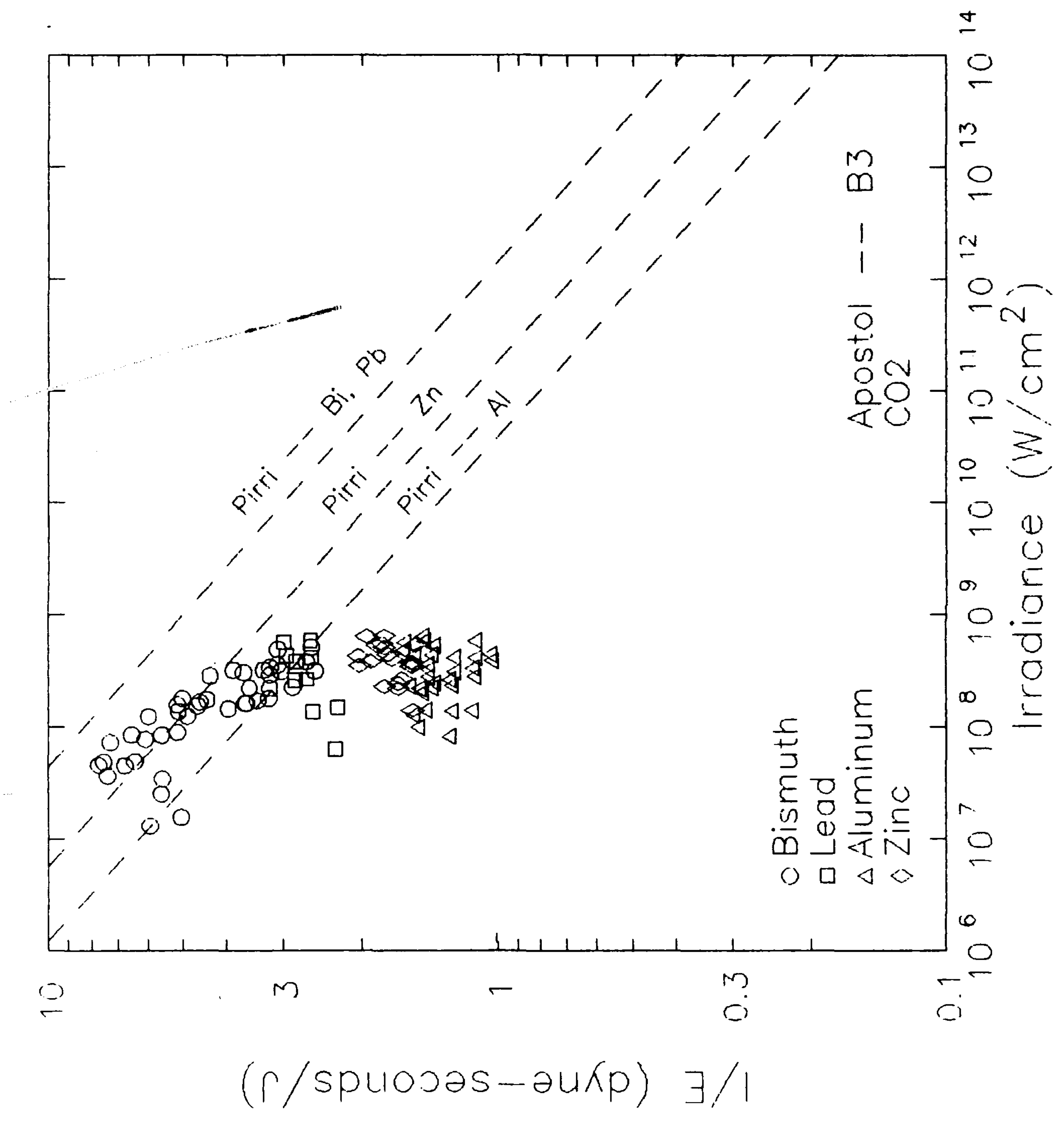
Target dimensions: not given

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Dependences of the specific recoil impulse I/E (different targets) . . . on the laser radiation intensity. . . "

Comments: These irradiance levels may be too low for the equilibrium vaporization regime. The order of the elements in impulse coupling coefficient -- according to the simple model, the coupling is proportional to the atomic weight to the power 7/18 -- is correctly predicted.



I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm^2)
10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14
Pirri --- Bi, Pb
Pirri --- Zn
Pirri --- Al
Bismuth
Lead
Aluminum
Zinc
Apostol — B3
CO2

Reference # : A04

Authors : D.I. Rosen, P.E. Nebolsine, P.K.S. Wu

Citation: "Laser impulse applications research", Paper V 1, AIAA Conference on Dynamics of High Power Lasers, Cambridge MA, 30 Oct 1978

Institution: Physical Sciences Inc., Andover MA

Experimental Conditions:
Laser: Lumonics 103-2 (e-beam CO_2)
Wavelength: 10.6 μm
Pulse energy: 12 J
Pulse duration: 3 μs
Intensity range:
Atmosphere: vacuum, 0.03 - 0.20 Torr (4 - 270 μbar)

Spot dimensions: variable, and unspecified, but evidently within the range 0.4 - 3 cm diameter

Target materials: Carbon phenolic, asbestos phenolic, silica phenolic, carbon-carbon, Teflon, ATJ-S graphite, aluminum foil on carbon phenolic, copper sheet on carbon phenolic, gold electroplated on graphite

Target dimensions: not specified

Measured quantities: impulse

Measurement technique: ballistic pendulum

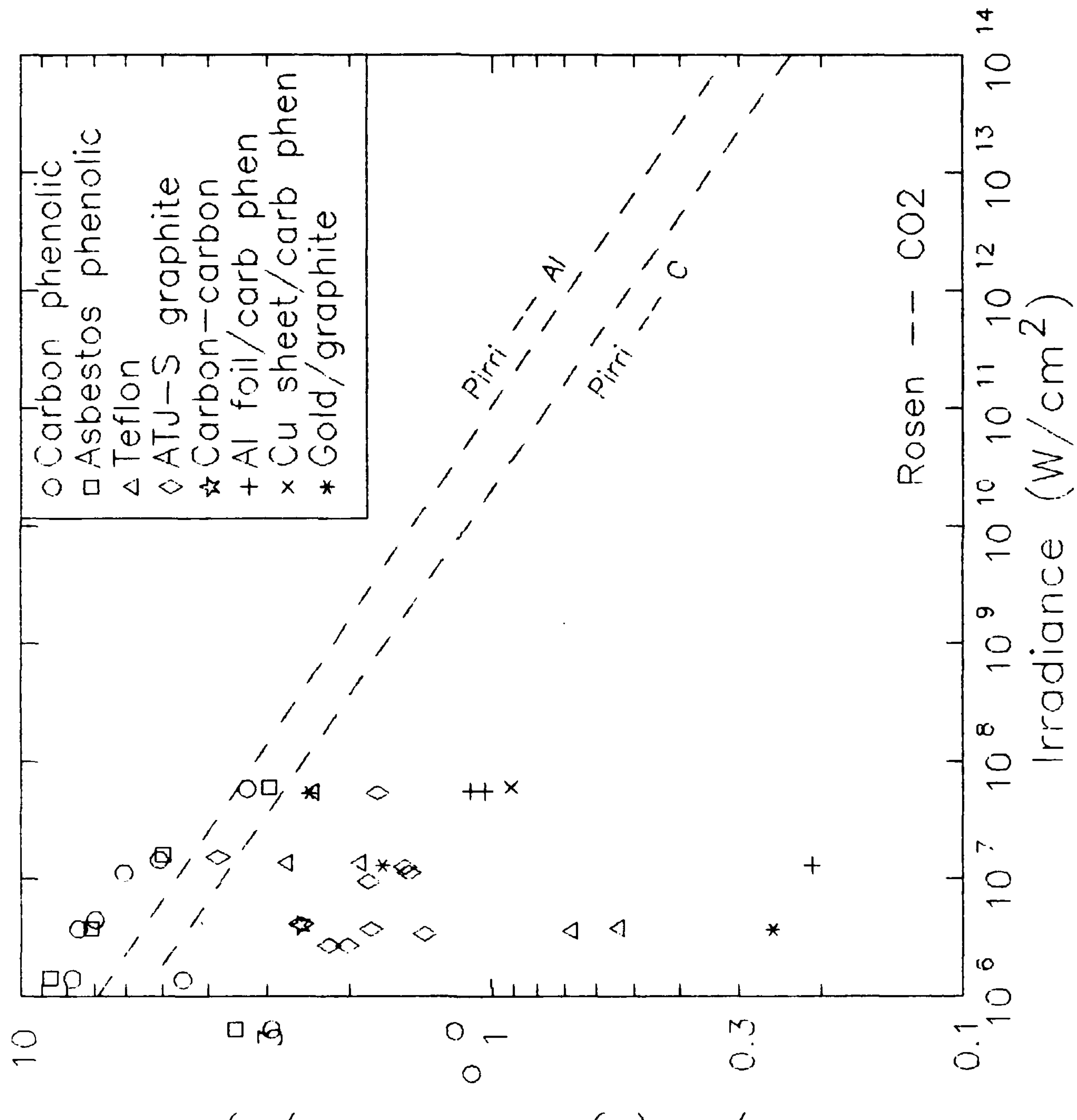
Figure caption: "Impulse coupling coefficient . . . "

Comments: Most of these data are at such low irradiance levels that the interaction is dominated by sub-plasma ablation, involving a complex of variables, i.e. vaporization kinetics, thermal conduction, and material absorptance. At the higher irradiances the widely scattered data tend to converge toward the Pirri lines.

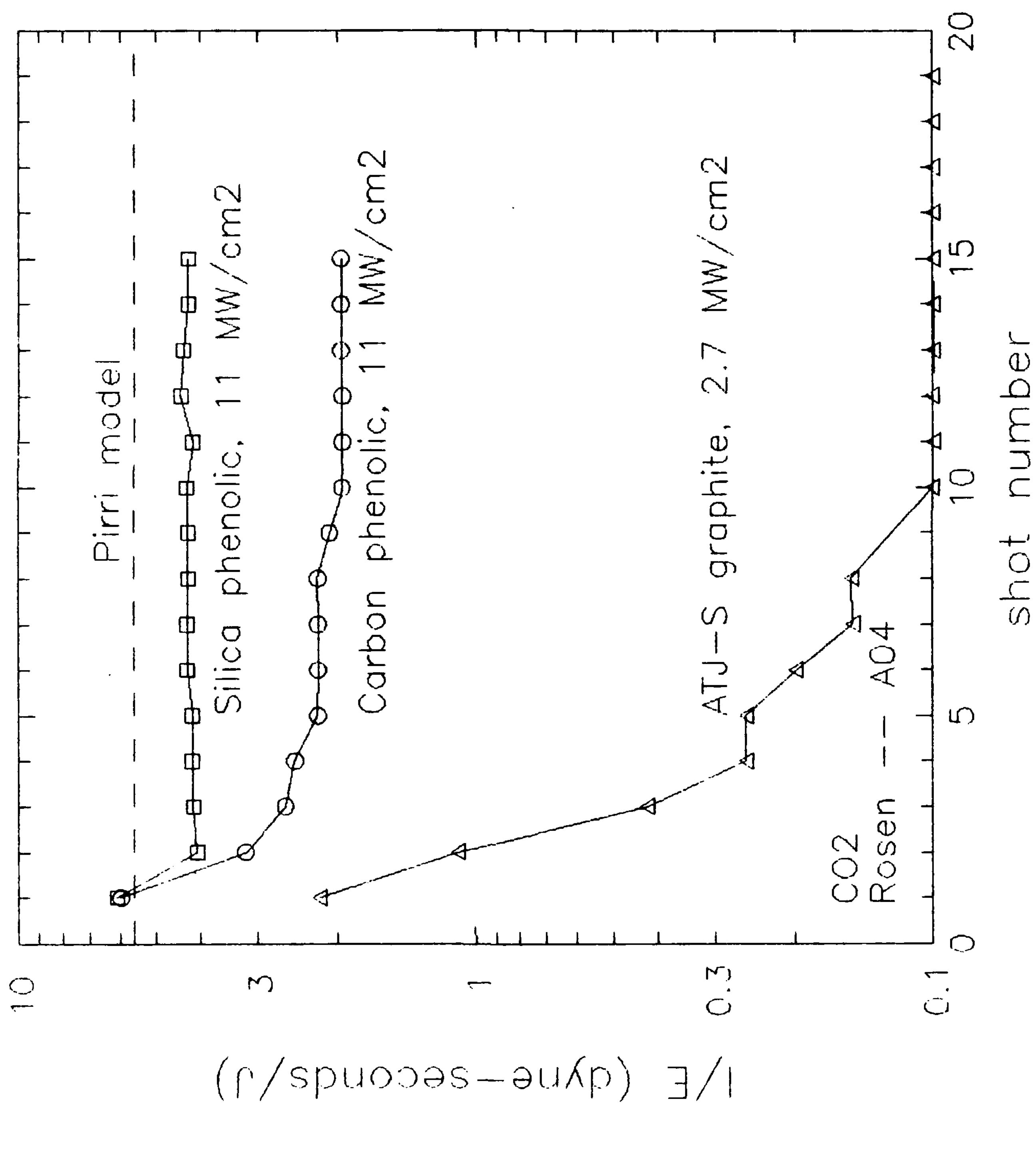
Numerous other I/E measurements are in Rosen's report, including coupling for a longer (12 μs) pulse and coupling as a function of pulse number for long pulse trains. Most of these data have not been included in this compilation due to the low irradiance levels and small pulse energies (only 2.5 J at the longer pulse duration), and the consequent complex, material-history-sensitive physics, which prevents reasonable extrapolation of these results to any other condition.

One set of sequential-irradiation data, at the higher irradiances applied by Rosen, is included here for illustration. The effect of repeated irradiation at low irradiance is to laser-clean the surface and gradually suppress plasma formation, decreasing the coupling to a very low value, clear on the ATJ-S specimen. At higher irradiance the laser-cleaning effect on ignition is not as pronounced; a substantial drop occurs after the first pulse, after which

the coupling stabilizes at a value well below the Pirri prediction. The high coupling for the first pulse is possibly due to surface particles being exploded by the irradiation. This suggests that a great deal of the impulse coupling data in hand is potentially higher than would be observed on a particle-free surface, and comparing first-pulse data to models assuming simple surfaces may be misleading.



Carbon phenolic
Asbestos phenolic
Teflon
ATJ-S graphite
Carbon-carbon
Carbon-carb phen
Al foil/carb phen
Cu sheet/carb phen
Gold/graphite
Pirri -- Al
Pirri -- C
Rosen -- CO2
Irradiance (W/cm²)
I/E (dyne-seconds/J)



Pirri model
Silica phenolic, 11 MW/cm2
Carbon phenolic, 11 MW/cm2
ATJ-S graphite, 2.7 MW/cm2
CO2
Rosen -- A04
I/E (dyne-seconds/J)
shot number
10
3
1
0.3
0.1
0
5
10
15
20

Reference # : B2

Authors : Ven H. Shui, Lee A. Young, and James P. Reilly

Citation: "Impulse transfer from pulsed CO_2 laser irradiation at reduced ambient pressures", AIAA Journal 16, 649-650 (1978)

Institution: Avco Everett Research Laboratory, Everett MA

Experimental Conditions:

Laser: TEA CO_2

Wavelength: 10.6 μm

Pulse energy: 110-270 J

Pulse duration: nominally 10 μs; 80% of energy in first 8-14 μs, remainder in 5-15 μs

Intensity range: 6 - 240 MW/cm^2

Atmosphere: 0.5 Torr

Spot dimensions: 0.38 - 2.3 cm diameter

Target Materials: Aluminum, 2024 alloy, bare and painted; carbon phenolic; carbon cloth

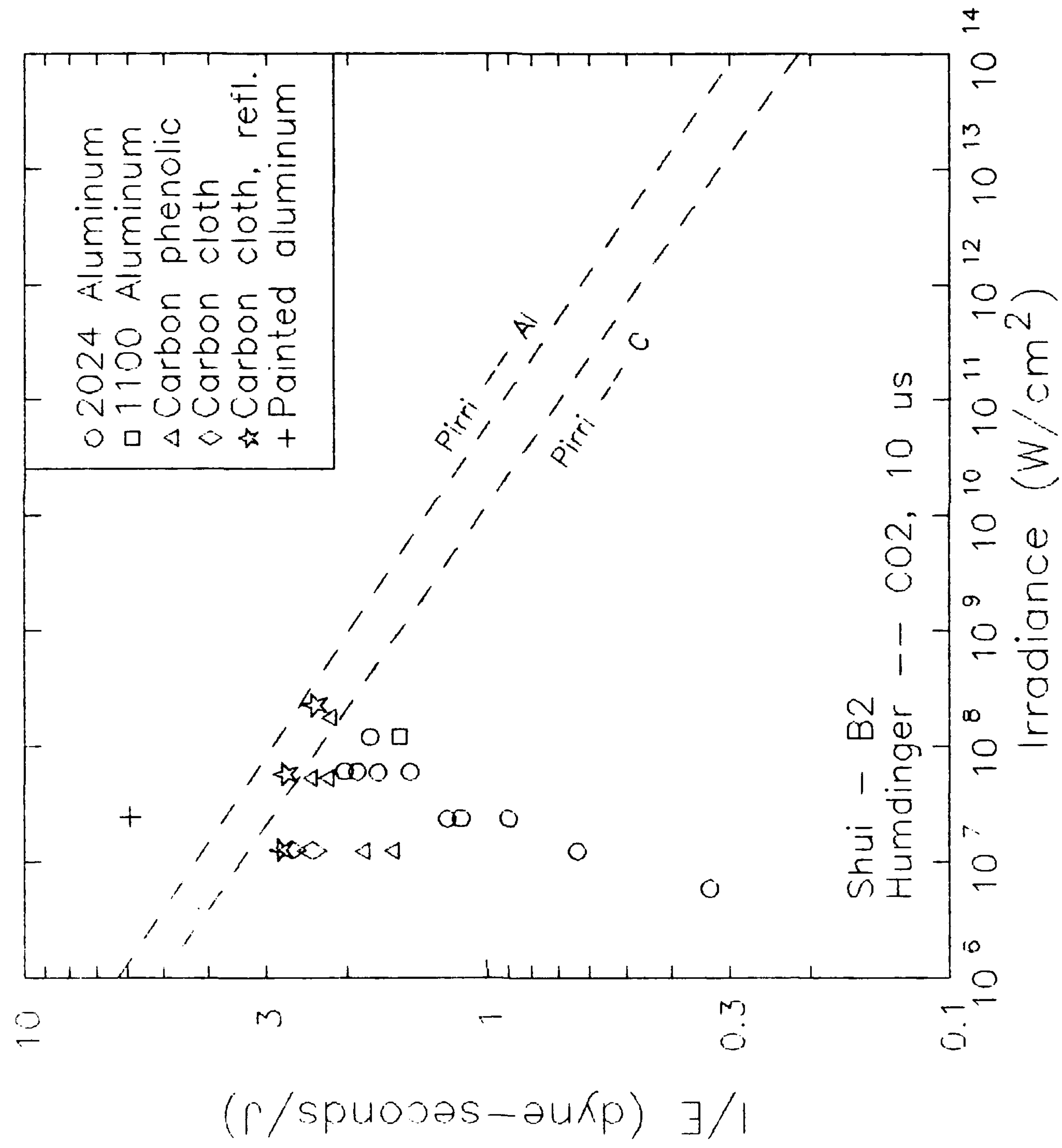
Target dimensions: 31 cm diameter

Measured quantities: total impulse

Measurement technique: ballistic pendulum

Figure caption: "Ratio of impulse imparted to varous targets to incident laser energy (impulse/energy coupling coefficient) as a function of fluence incidence on target, at 0.5 Torr absolute pressure. . . ."

Comments: Thermal coupling work on a similar laser suggests that the transition from the air interaction to a vacuum interaction occurs at 2 Torr ambient pressure, so this set of data should represent the vacuum interaction. The values observed are consistent with that interpretation. The low values on bare aluminum indicate energy losses to marginal plasma ignition. The high value on painted aluminum is perhaps due to explosive (non-vaporizing) paint removal.



○ 2024 Aluminum
□ 1100 Aluminum
△ Carbon phenolic
◇ Carbon cloth
☆ Carbon cloth, refl.
+ Painted aluminum
Pirri -- Al
Pirri -- C
Shui - B2
Humdinger -- CO2, 10 us
Irradiance (W/cm2)
I/E (dyne-seconds/J)

Reference # : B30

Authors : I. Ursu, I. Apostol, D. Barbulescu, I.N. Mihailescu, M. Moldovan, A.M. Prokhorov, V.P. Ageev, A.A. Gorbunov, and V.I. Konov

Citation: "The vaporization of a metallic target by a microsecond pulsed TE-CO_2 laser radiation", Optics Commun. 39, 180-185 (1981).

Institution: Central Institute of Physics, Bucharest Romania, and Lebedev Physics Institute, Moscow USSR

Experimental Conditions:

Laser: TEA CO_2

Wavelength: 10.6 μm

Pulse energy: 50 J

Pulse duration: 100 ns spike plus 2 μs tail

Intensity range: 4×10^8 - 1×10^9 W/cm^2

Atmosphere: vacuum, 0.01 Torr (13 μbar)

Spot dimensions: 0.01 cm^2 area

Target material: stainless steel

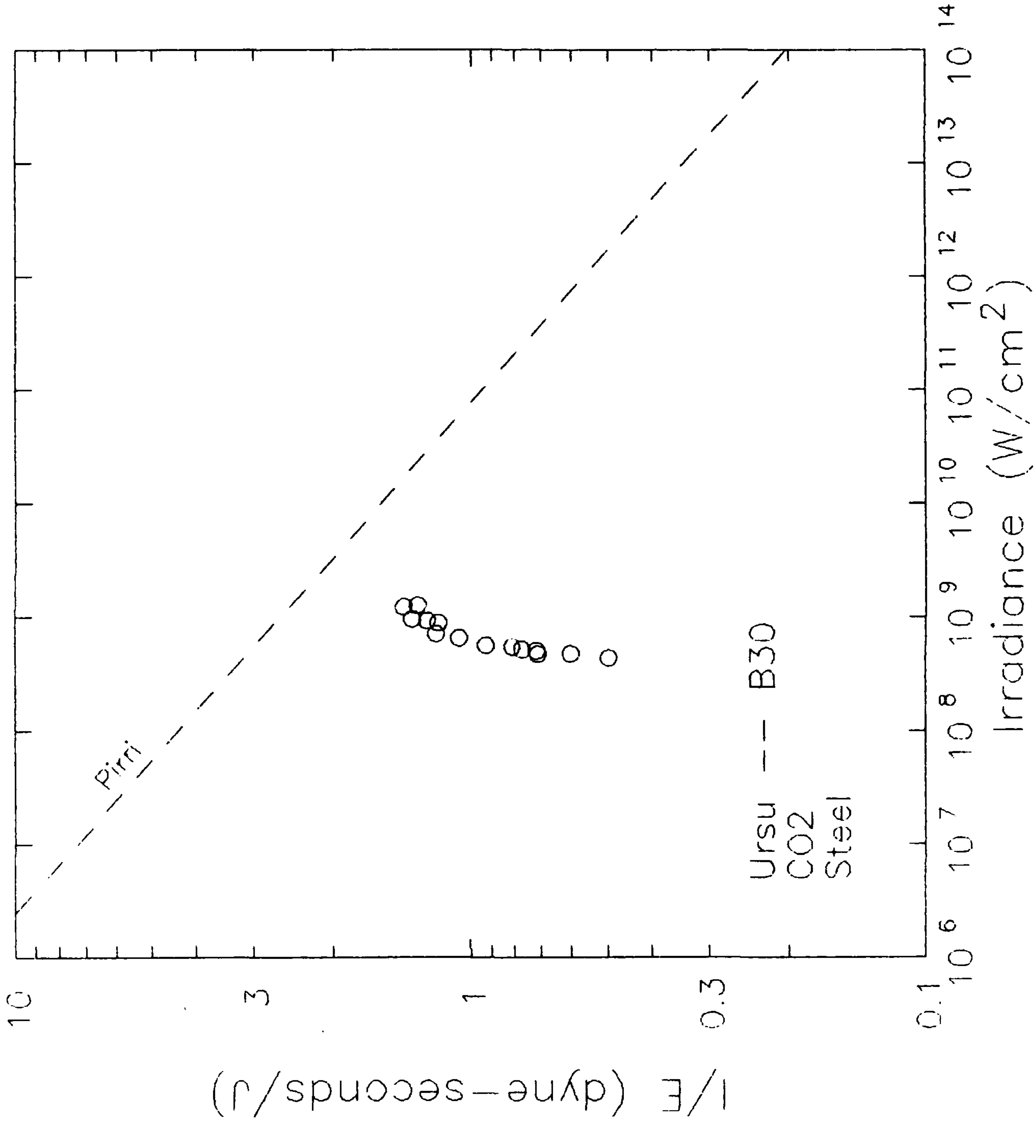
Target dimensions: not given

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum

Figure caption: "Variation of the specific recoil momentum I/E, as a function of energy density E/A and maximum intensity in laser pulse, I(max)."

Comments: These data appear to be strongly affected by threshold losses.



I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Irradiance (W/cm^2)
Pirri
Ursu — — B30
CO2
Steel

Reference # : GEM1

Authors : C.R. Phipps, T.R. King, and R.S. Dingus

Citation: Unpublished viewgraphs from a presentation to the Air Force Space Division, dated 18 October 1984

Institution: Los Alamos National Laboratory, Los Alamos NM

Experimental Conditions:

Laser: Los Alamos Gemini

Wavelength: 10.6 μm

Pulse energy: 3 kJ

Pulse duration: 1.8 μs

Intensity range: 1×10^7 - 1×10^9 W/cm^2

Atmosphere: vacuum, unspecified

Spot dimensions: unspecified

Target materials: Aluminum, titanium, Kevlar epoxy, carbon phenolic, Vamac, Lucite, "LRN"

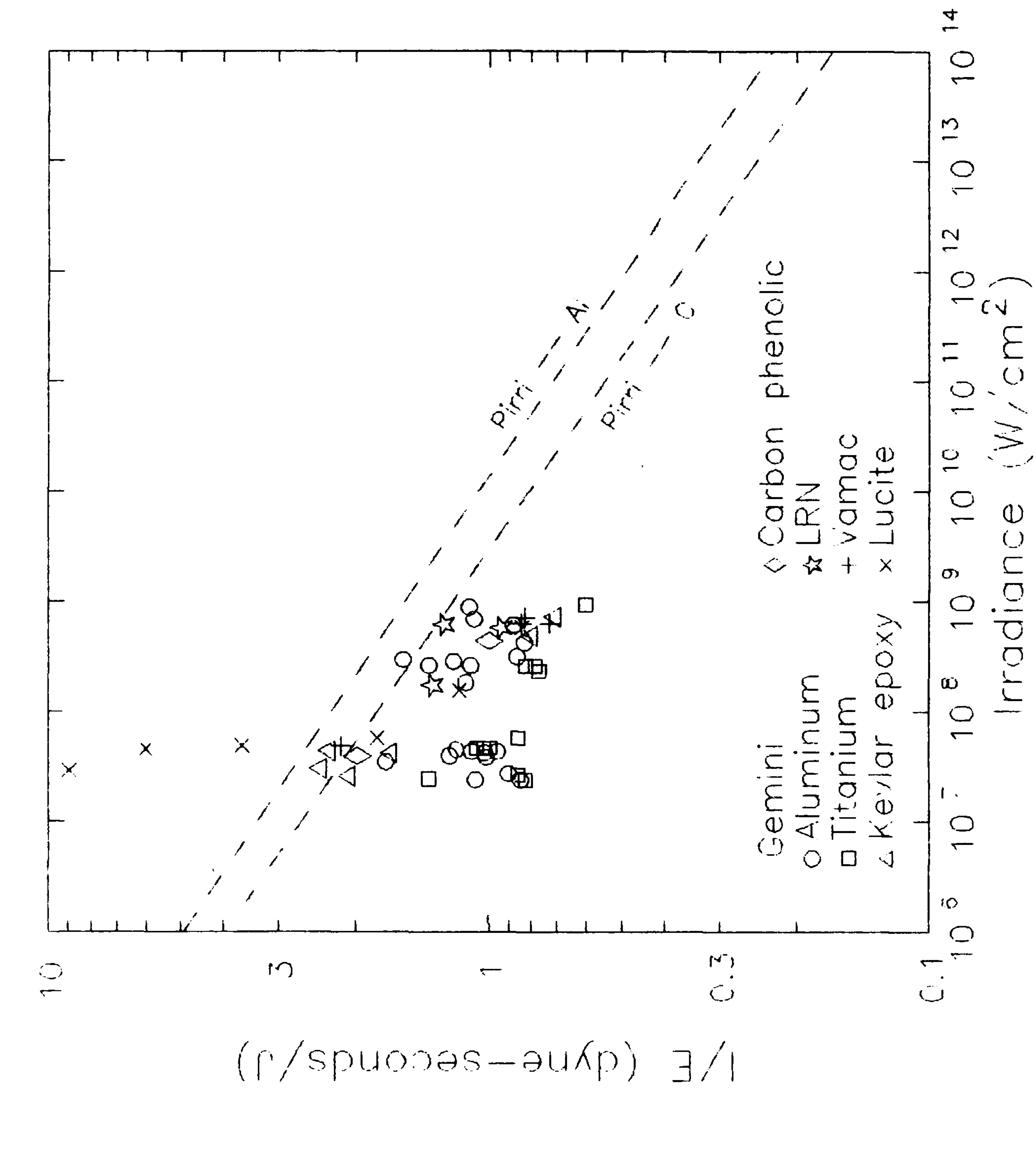
Target dimensions: not specified

Measured quantities: impulse

Measurement technique: Not specified

Figure caption: "Gemini Unstable Resonator coupling coefficient data".

Comments: We have assumed that this experiment was performed with fixed laser pulse energy and variable spot size, since that has been the practice by LANL workers and because pulse energy variation with large CO_2 lasers is very difficult. With the prominent exception of Lucite, the data show the appropriate irradiance dependence, but are consistently lower than the Pirri model prediction. Lucite evidently includes some impulse generation by explosive material removal, due to in-depth laser absorption. The removal of mass by solid- or liquid-state expulsion is an impulse generator of substantially higher efficiency than is removal by vaporization.



I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Irradiance (W/cm^2)
Pirri -- Al
Pirri -- C
Gemini
○ Aluminum
□ Titanium
△ Kevlar epoxy
◇ Carbon phenolic
☆ LRN
+ Vamac
× Lucite

Reference # : GEM2

Authors : C.R. Phipps, T.R. King, and R.S. Dingus

Citation: Unpublished viewgraphs from a presentation to the Air Force Space Division, dated 18 October 1984

Institution: Los Alamos National Laboratory, Los Alamos NM

Experimental Conditions:
Laser: Los Alamos Gemini
Wavelength: 10.6 μm
Pulse energy: 1 kJ
Pulse duration: 2 ns
Intensity range: 1×10^{11} - 2×10^{11} W/cm^2
Atmosphere: vacuum, unspecified

Spot dimensions: unspecified; evidently about 2.5 cm diameter

Target materials: Titanium, "other materials"

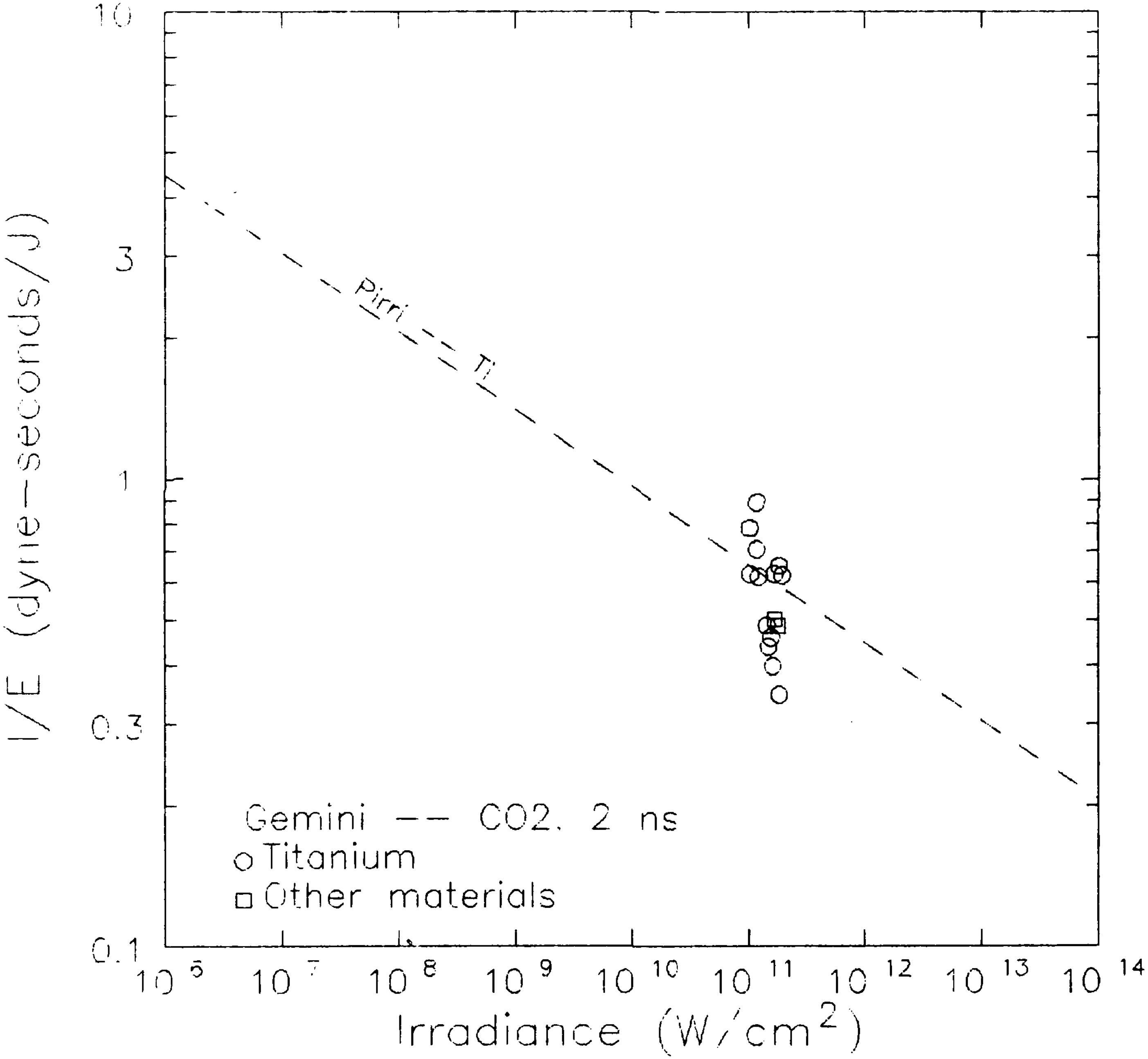
Target dimensions: not specified

Measured quantities: impulse

Measurement technique: Not specified

Figure caption: "Gemini coupling coefficient data".

Comments: With this very short pulse and relatively large spot, the radial-equilibrium conditions assumed by the Pirri model cannot possibly be satisfied, the time for material flow to the spot perimeter being at least two orders of magnitude greater than the pulse duration. The model nevertheless yields values within the range of those observed. The intensity range covered by this experiment is insufficient for the drawing of conclusions concerning irradiance dependence.


I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Pirri -- Ti
Gemini -- CO2. 2 ns
○ Titanium
□ Other materials
10 5
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
Irradiance (W/cm 2)

Reference # : MJOL

Authors : C.R. Phipps, T.R. King, and R.S. Dingus

Citation: Unpublished viewgraphs from a presentation to the Air Force Space Division, dated 18 October 1984

Institution: Los Alamos National Laboratory, Los Alamos NM

Experimental Conditions:
Laser: Mjollnir, e-beam pumped HF/DF (AFWL)
Wavelength: 2.7-3.2 μm
Pulse energy: 3 kJ
Pulse duration: 1.6 μs
Intensity range: 1×10^8 - 1×10^9 W/cm^2
Atmosphere: vacuum, unspecified

Spot dimensions: unspecified

Target materials: Aluminum, titanium, Kevlar epoxy, carbon phenolic, Vamac, TBR, HARF 3, HARF 7

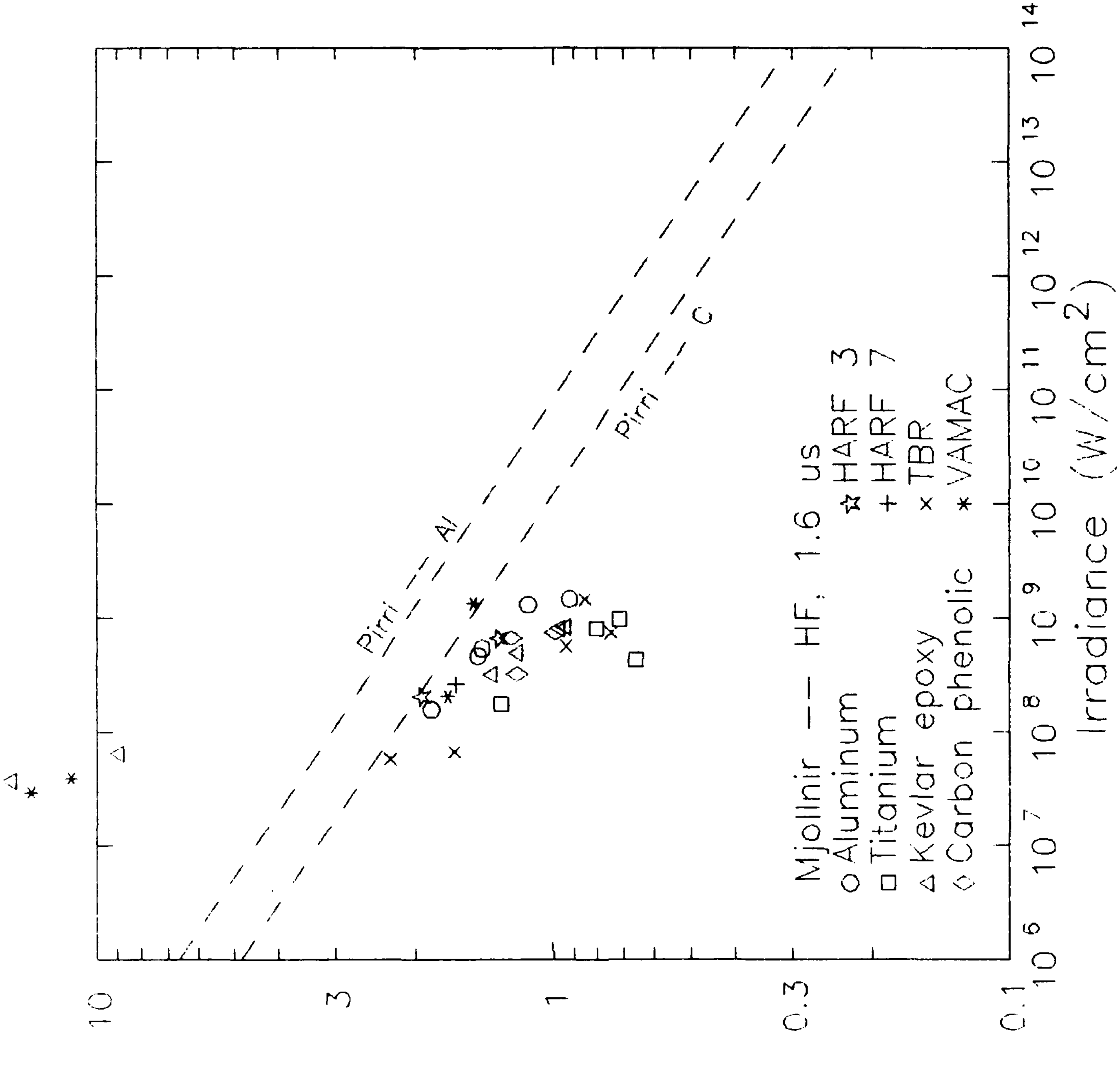
Target dimensions: not specified

Measured quantities: impulse

Measurement technique: Not specified

Figure caption: "Mjollnir coupling coefficient data"

Comments: These are the highest-pulse-energy HF data known to us. As for other large-spot experiments, the data tend to lie under the Pirri curve, with a few prominent exceptions. Impulse generation by mass expulsion associated with in-depth laser absorption is the likely cause of the very high impulse coupling values; note the data points above the limit of the plot.



Mjollnir — HF, 1.6 us
o Aluminum
□ Titanium
△ Kevlar epoxy
◇ Carbon phenolic
☆ HARF 3
+ HARF 7
× TBR
* VAMAC
Pirri — Al
Pirri — C
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm^2)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

Reference # : B4

Authors : Ralph R. Rudder, Jay A. Howland, and Arnold L. Augustoni

Citation: "Impulse production by expanding blast waves", AFWL TR-72-243, pp. 92-96 (Dec 1972)

Institution: Air Force Weapons Laboratory

Experimental Conditions:

Laser: Nd:glass (amplified spontaneous emission type)

Wavelength: 1.06 μm

Pulse energy: 100 J

Pulse duration: 1.1 μs

Fluence range: 8 - 120 J/cm^2

Atmosphere: 1 atm air and vacuum (25 μm Hg)

Spot dimensions: 0.92 cm diam

Target materials: Titanium 6Al-4V

Target dimensions: 1.59, 2.54, 5.08 cm diam disks

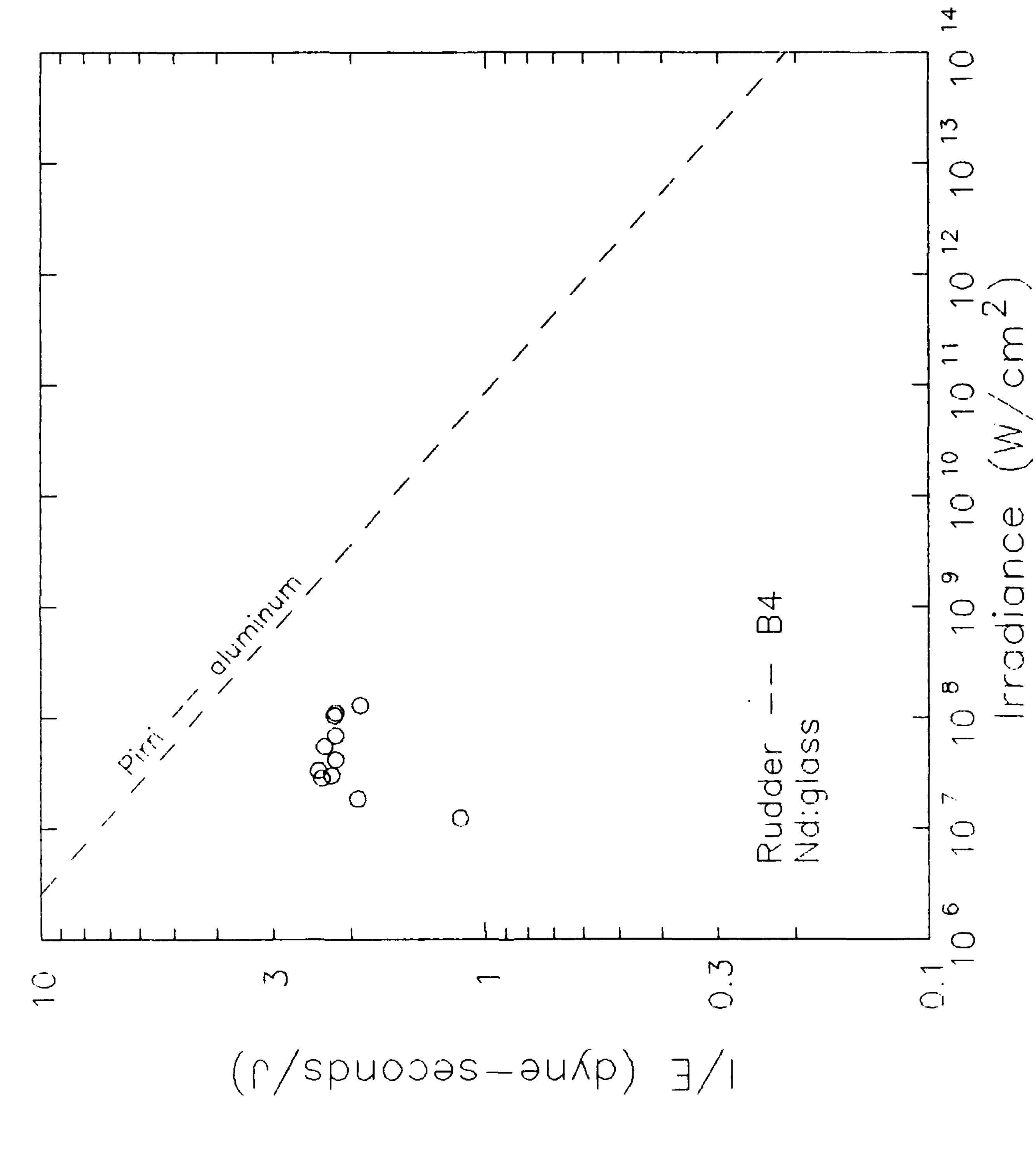
Measured quantities: Impulse

Measurement technique(s): LVT

Figure caption: "Total impulse, measured with LVT gauge, imparted to titanium (6Al-4V) discs of diameter 3/8-inch, 1-inch, and 2 inches, versus laser fluence . . ."

Comments: "These experiments have shown for 1.06-μ pulses of duration 1.1 μs that the momentum transferred to titanium targets increases with increasing target diameter for fluxes greater than about 3x10^7 W/cm^2. No similar target-size dependence was noted for vacuum interactions, and the momentum transfer was reduced."

The vacuum data lie well below the Pirri line, possibly due to threshold effects.



I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14
Irradiance (W/cm^2)
Pirri --- aluminum
Rudder --- B4
Nd:glass

Reference # : B32

Authors: S.A. Metz

Citation: "Impulse loading of targets by subnanosecond laser pulses", Appl. Phys. Lett. 22, 211-213 (1973)

Institution: Naval Research Laboratory, Washington DC

Experimental Conditions:

Laser: Nd:YAG

Wavelength: 1.06 μm

Pulse energy: 25 J

Pulse duration: 0.25 ns

Intensity range: to 1.4×10^{10} W/cm^2

Atmosphere: 1 atm air, and vacuum (under 100 μm Hg)

Spot dimensions: 1.5 cm diam

Target materials: aluminum (1100), carbon (POCO AXF-5Q graphite)

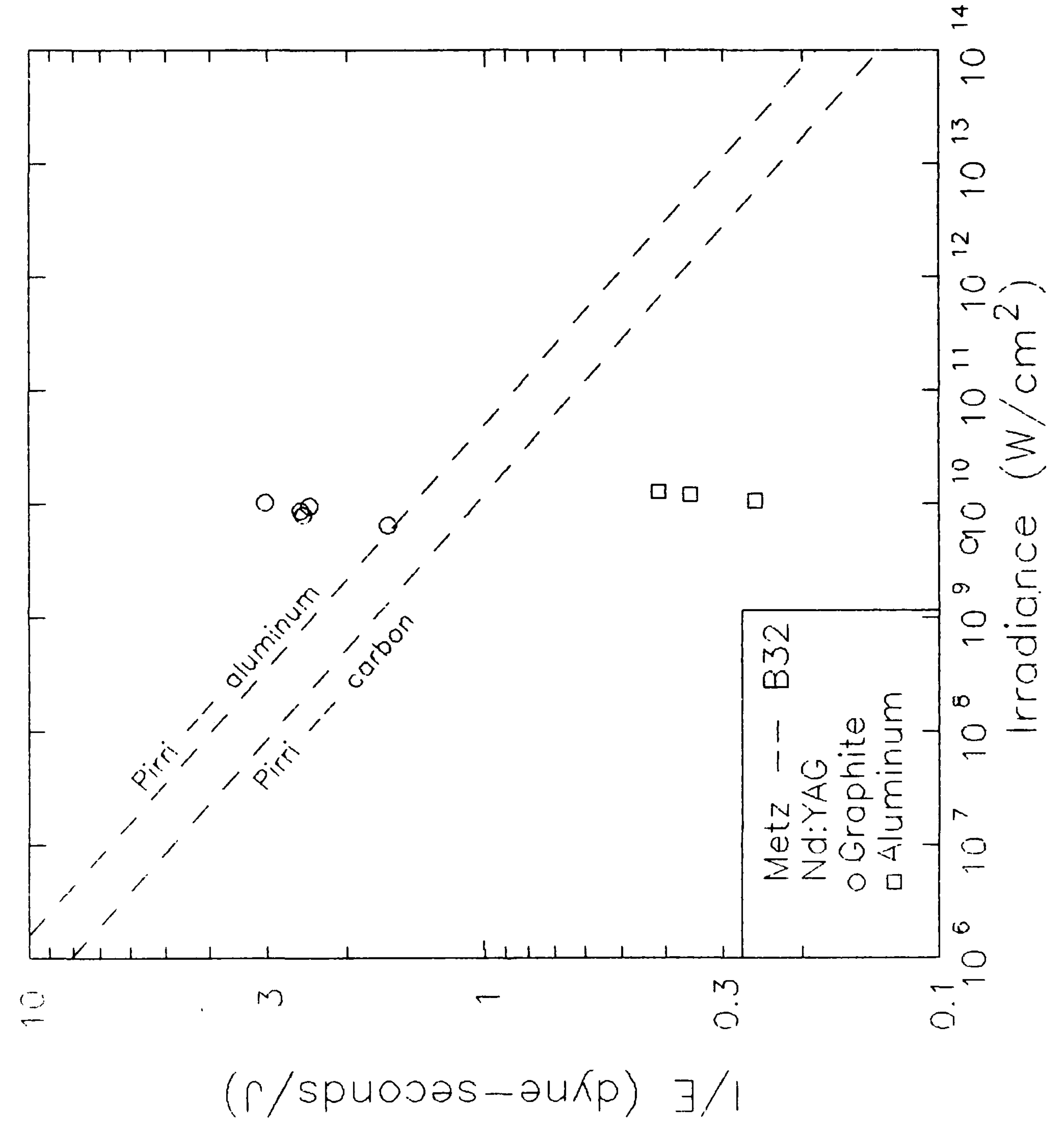
Target dimensions: 4 cm diam (Al), 4 cm square (C)

Measured quantities: total impulse

Measurement technique(s): rotation of potentiometer shaft

Figure caption: *Figure 2: Impulse vs. incident energy. Graphite target.* 250-psec pulse. Figure 3: Impulse vs. incident energy. Aluminum target. 250-psec pulse.

Comments: Impulse delivery by this very short, large-diameter spot shows little resemblance to the Pirri model predictions. This is not surprising since the latter assumes a strongly two-dimensional interaction while this experiment is extremely one-dimensional.



I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm²)
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴
Pirri -- aluminum
Pirri -- carbon
Metz -- B32
Nd:YAG
Graphite
Aluminum

Reference # : B40

Authors : R. R. Rudder

Citation: "Vacuum interaction of pulsed 1-micron radiation with solid matter", AFWL TR-74-100 (1974)

Institution: Air Force Weapons Laboratory, Albuquerque NM

Experimental Conditions:

Laser: amplified spontaneous emission Nd:glass

Wavelength: 1.06 μm

Pulse energy: 125 J

Pulse duration: 1, 5, 20, 100 μs

Intensity range: 1×10^6 - 2×10^8 W/cm^2

Atmosphere: vacuum, less than 10 microns Hg (13 μbars)

Spot dimensions: 0.65 cm diameter

Target materials: 2024-T3 Al, Grafoil, titanium 6Al-4V

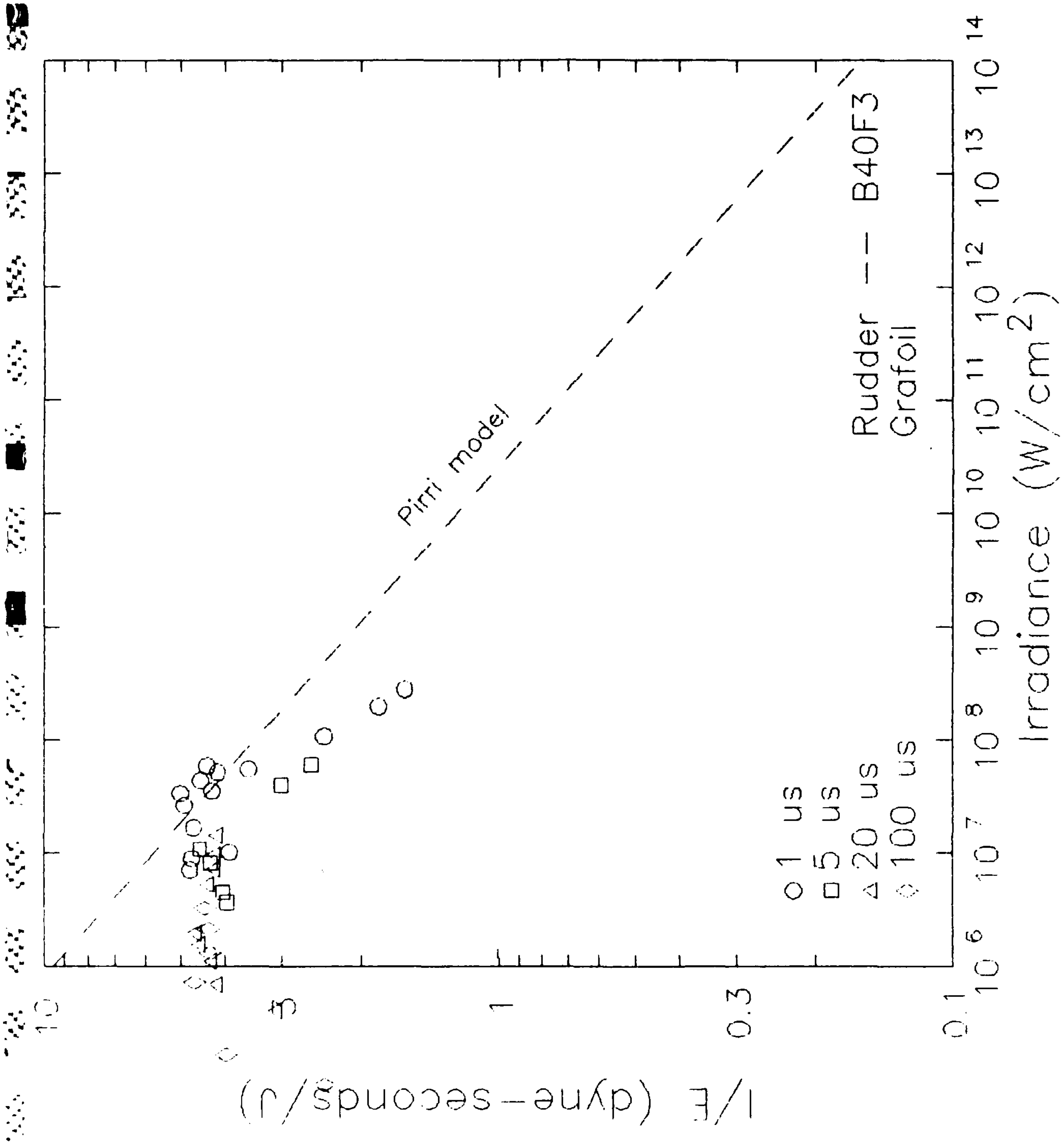
Target dimensions: 1.588 cm diameter disks

Measured quantities: total impulse

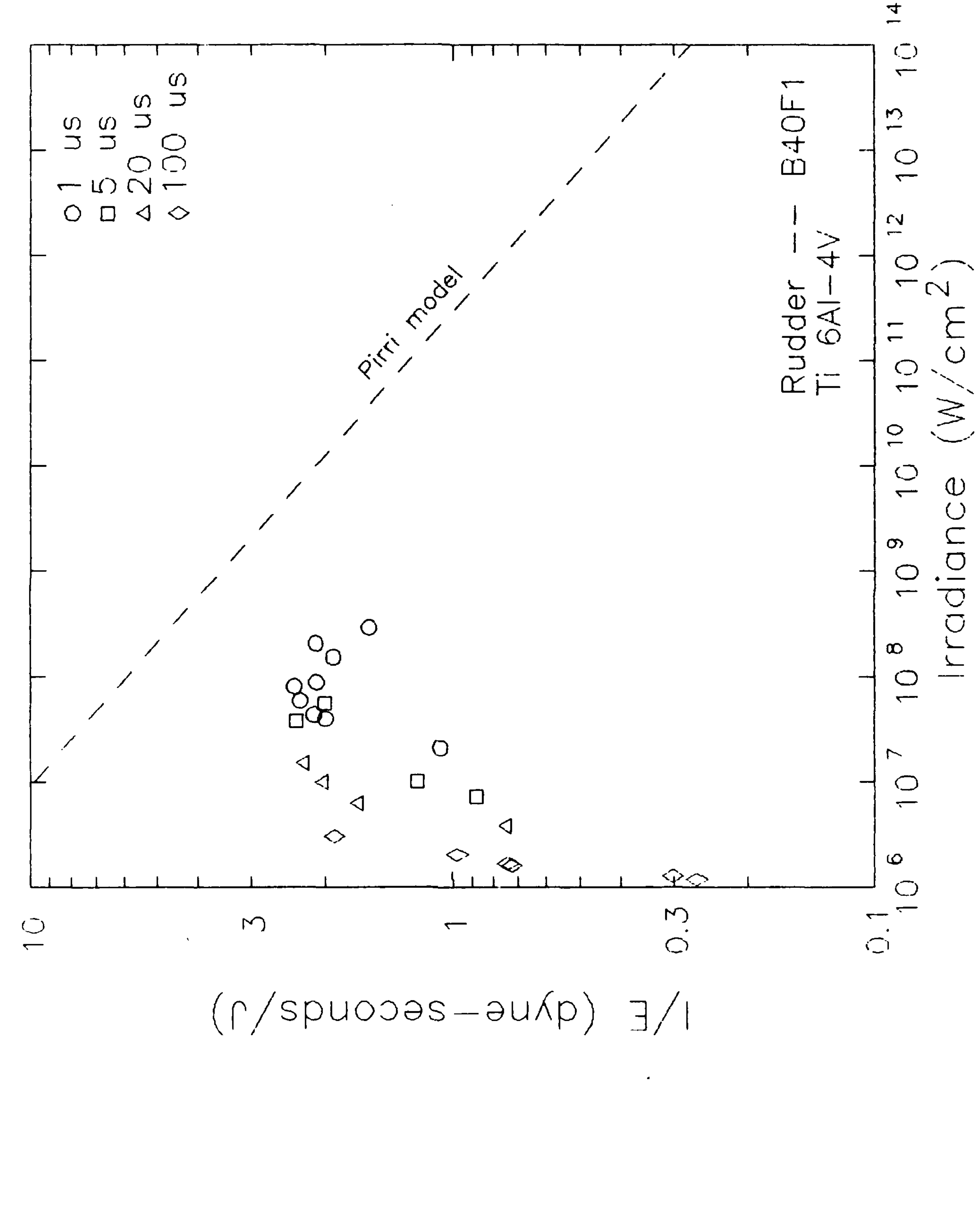
Measurement technique(s): linear velocity transducer

Figure caption: "Total momentum transfer to 0.625-inch diameter discs of [titanium, aluminum, Grafoil] in vacuum versus incident energy for pulse durations of 1 μs, 5 μs, 20 μs, and 100 μs. . . "

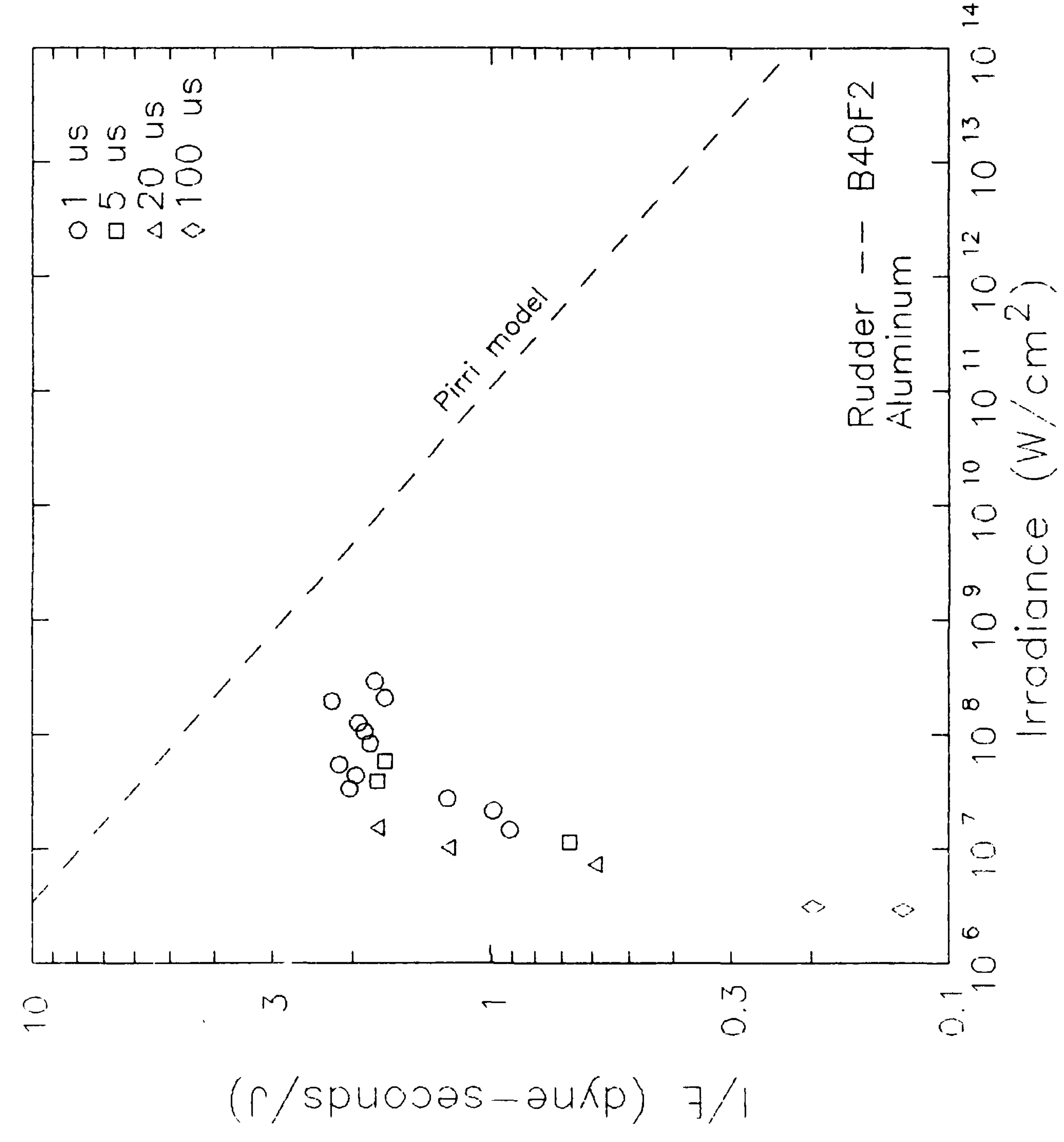
Comments: These low-irradiance data indicate coupling reduced by plasma threshold losses. Transparent-vapor target ablation is probably the principal mechanism of impulse generation.



I/E (dyne-seconds/J)
Irradiance (W/cm²)
Pirri model
Rudder --- B40F3
Grafoil
○ 1 us
□ 5 us
△ 20 us
◇ 100 us
10
1
0.3
0.1
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14



I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm2)
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
Pirri model
o 1 us
□ 5 us
△ 20 us
◇ 100 us
Rudder -- B40F1
Ti 6Al-4V


I/E (dyne−seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Irradiance (W/cm^2)
Pirri model
○ 1 us
□ 5 us
△ 20 us
◇ 100 us
Rudder --- B40F2
Aluminum

Reference # : B26

Authors : S. Zweigenbaum, Y. Gazit and Y. Komet

Citation: "Momentum measurements of laser produced plasma", Plasma Physics 19, 1035-1042 (1977).

Institution: Soreq Nuclear Research Centre, Yavne, Israel

Experimental Conditions:
Laser: Nd:glass
Wavelength: 1.06 μm
Pulse energy: 15 J
Pulse duration: 0.5 ns
Intensity range: 2×10^{12} - 4×10^{13} W/cm^2
Atmosphere: vacuum, 10^{-5} Torr (0.01 μbar)

Spot dimensions: 0.011 cm diameter

Target materials: Aluminum foils

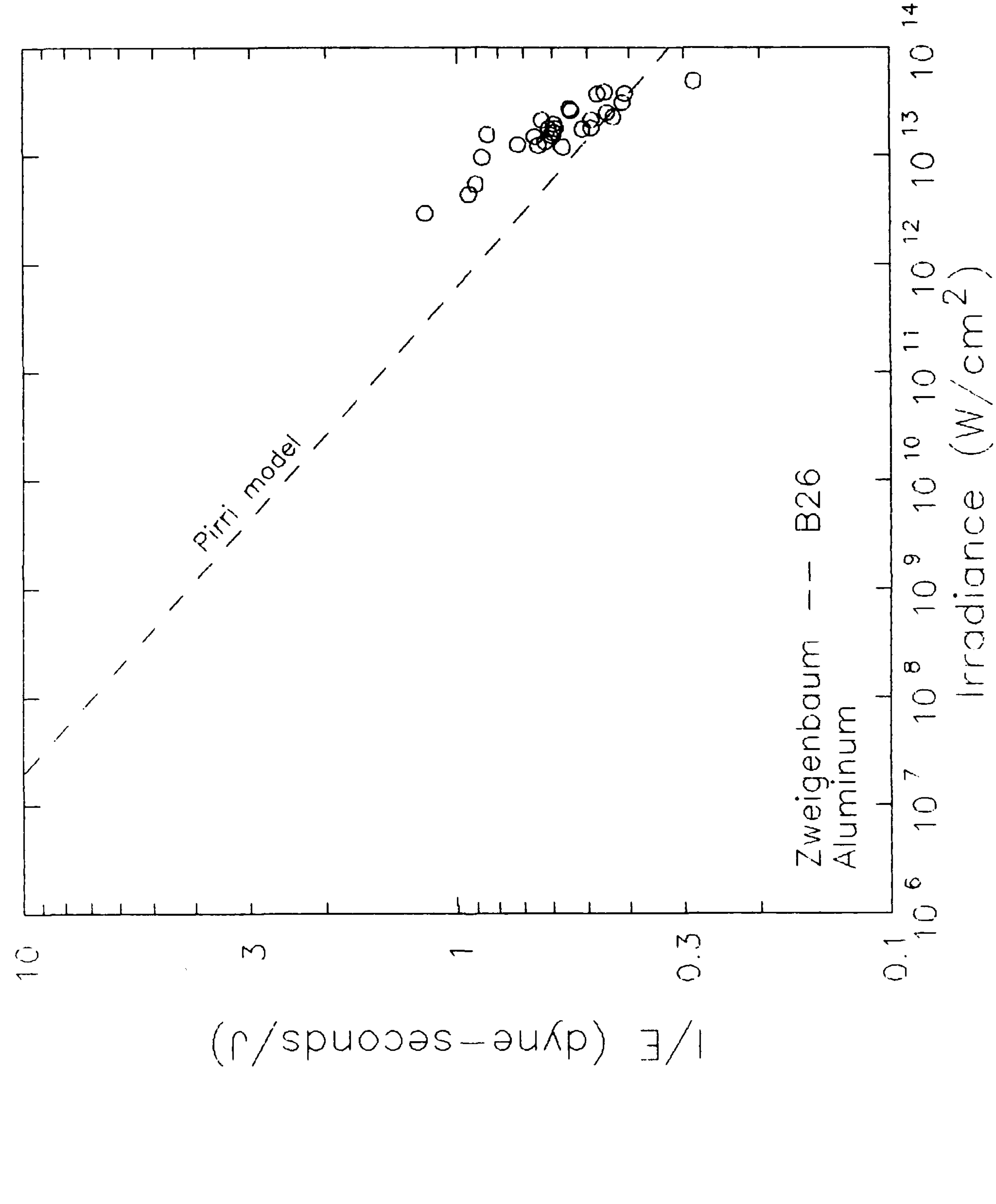
Target dimensions: very large compared to laser spot (centimeters)

Measured quantities: total impulse

Measurement technique(s): torsion pendulum

Figure caption: "Results of the recoil momentum of an Al target 1 mm thick. . ."

Comments: These high-irradiance data are very similar to those by Arad et al. (B25) on the same laser. The -2/9 irradiance dependence of impulse coupling appears to be well supported.



Zweigenbaum -- B26
Aluminum
Pirri model
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14

Reference # : B25

Authors : B. Arad, S. Eliezer, Y. Gazit, H.M. Loebenstein, A. Zigler, H. Zmora, and S. Zweigenbaum

Citation: "Burn-through of thin aluminum foils by laser-driven ablation", J. Appl. Phys. 50, 6817-6821 (1979)

Institution: Soreq Nuclear Research Centre, Yavne, Israel

Experimental Conditions:
- Laser: Nd:glass
  - Wavelength: 1.06 μm
  - Pulse energy: 15 J
  - Pulse duration: 0.5 ns
- Intensity range: 4×10^{12} - 1×10^{14} W/cm^2
- Atmosphere: vacuum, residual pressure not specified

Spot dimensions: 0.02 cm diameter

Target materials: Aluminum foils

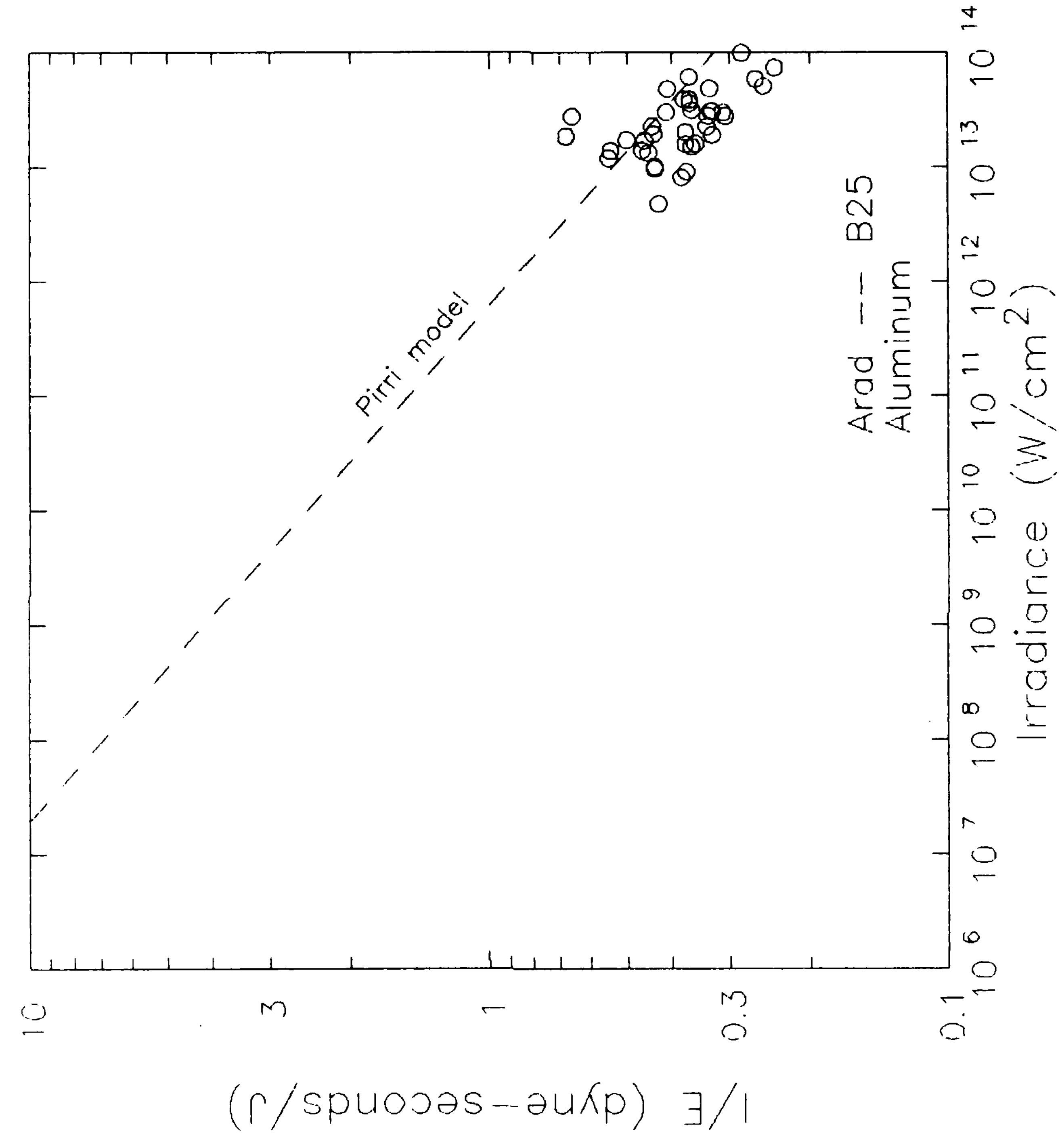
Target dimensions: very large compared to laser spot (centimeters)

Measured quantities: total impulse

Measurement technique(s): torsion pendulum

Figure caption: "The plasma momentum as a function of laser energy and irradiance . . ."

Comments: These high-irradiance data support the intensity scaling predicted by the Pirri (and numerous other) models, namely that the impulse coupling should be proportional to the -2/9 power of the laser irradiance.


Pirri model
Arad — B25
Aluminum
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

Reference # : B6

Authors : G.A. Askar'yan and B.M. Manzon

Citation: "Recoil momentum and laser-jet acceleration caused by laser pulses of various lengths; acceleration with a moving focus", Sov. J. Plasma Phys. 7, 134-141 (1981).

Institution: Lebedev Physics Institute, Moscow USSR

Experimental Conditions:

- Laser: Q-switched Nd:glass
  - Wavelength: 1.06 μm
  - Pulse energy: 130 J
  - Pulse duration: 60 ns, 400 ns, and 4000 ns
- Intensity range: 2×10^{9} - 5×10^{11} W/cm^2
- Atmosphere: vacuum, unspecified

Spot dimensions: 80% of laser pulse energy in 0.064 cm diameter (60 ns pulse), 0.058 cm diameter (400 ns pulse), 0.062 cm diameter (4 μs pulse).

Target material: steel; no better specification

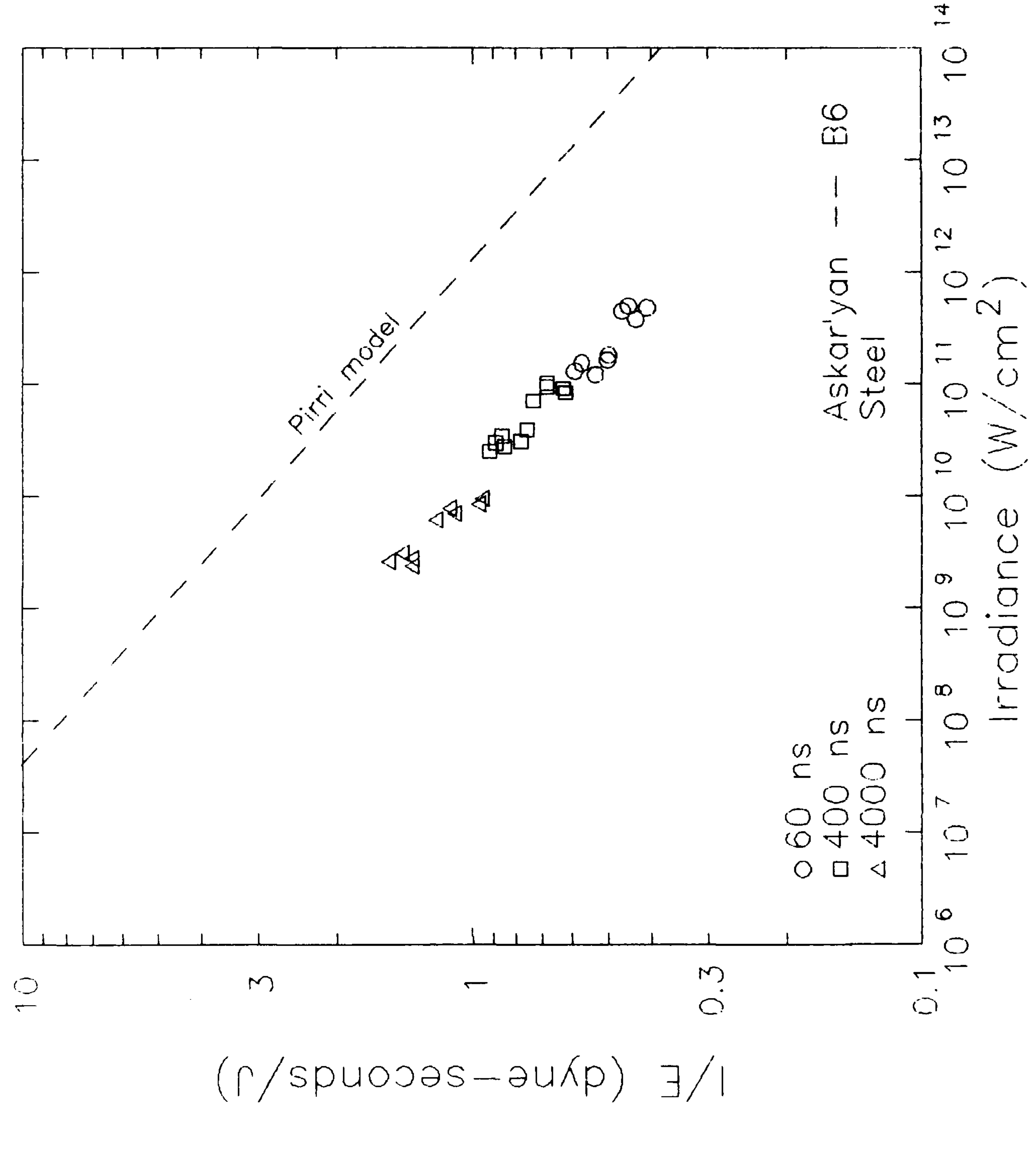
Target dimensions: 1.4 cm diam sphere

Measured quantities: total impulse

Measurement technique(s): pendulum

Figure caption: "Energy dependence of the recoil momentum for three pulse lengths."

Comments: The authors make much of the effect of pulse duration in generating "more efficient and smoother acceleration" of targets. When graphed against laser intensity the three pulse durations define a single line, suggesting that there is no pulse duration effect, only the intensity effect on coupling. The data lie well below the Pirri line, though the slope is in good agreement with the -2/9 prediction.



Pirri model
Askar'yan --- B6
Steel
○ 60 ns
□ 400 ns
△ 4000 ns
Irradiance (W/cm²)
I/E (dyne-seconds/J)

Reference # : GRUN

Authors : J. Grun, R. Decoste, B.H. Ripin, and J. Gardner

Citation: Appl. Phys. Lett. 39, 545-547 (1981)

Institution: Naval Research Laboratory, Washington DC

Experimental Conditions:
- Laser: Nd:glass (NRL Pharos II)
  - Wavelength: 1.05 μm
  - Pulse energy: approx. 350 J (not specified)
  - Pulse duration: 4 ns fwhm
- Intensity range: 4×10^{11} - 2×10^{13} W/cm^2
- Atmosphere: vacuum, unspecified

Spot dimensions: 1.0, 1.2 mm diameter

Target materials: polystyrene

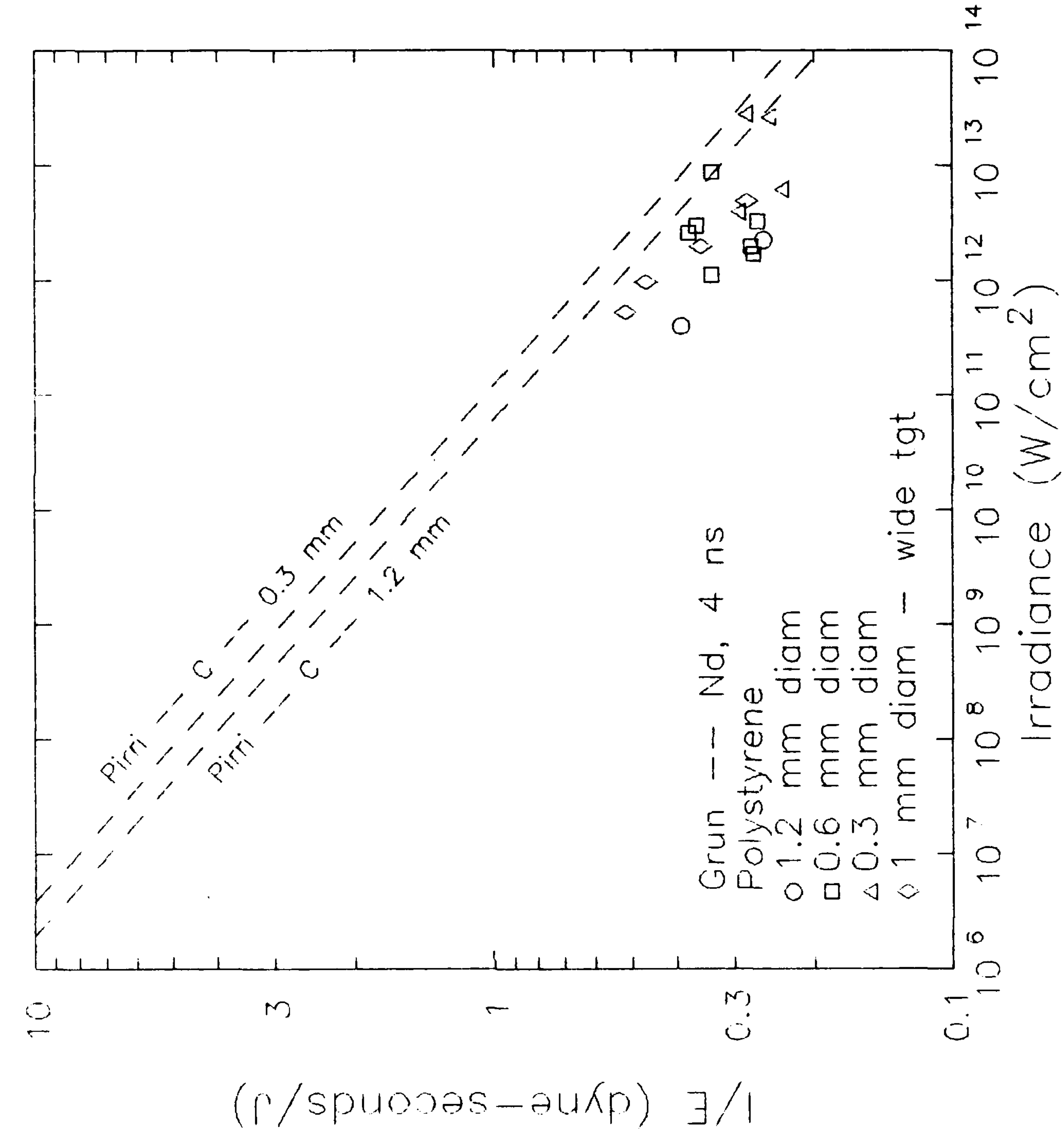
Target dimensions: 0.3, 0.6, 1.2 mm diameter (smaller than laser spot), except for 1 mm laser spot for which "wide" targets were used

Measured quantities: total impulse

Measurement technique(s): ballistic pendulum; confirmed by detection of plasma impulse from calorimeters and time-of-flight detectors

Figure caption: "Ablation pressure versus absorbed laser irradiance for disks and wide foil targets. . ."

Comments: Like most other impulse data, these values are close to but lower than the Pirri model line.



I/E (dyne-seconds/J)
Irradiance (W/cm²)
Pirri --- C --- 0.3 mm
Pirri --- C --- 1.2 mm
Grun --- Nd, 4 ns
Polystyrene
o 1.2 mm diam
□ 0.6 mm diam
Δ 0.3 mm diam
◇ 1 mm diam - wide tgt

Reference # : MEYER1

Authors : B. Meyer and G. Thiell

Citation: "Experimental scaling laws for ablation parameters in plane target-laser interaction with 1.06 μm and 0.35 μm laser wavelengths", Phys. Fluids 27, 302-311 (1984).

Institution: Commissariat a l'Energie Atomique, Centre d'Etudes de Limeil, Villeneuve-Saint-Georges, France

Experimental Conditions:

Laser: Nd:glass

Wavelength: 1.06 μm

Pulse energy: 100 J

Pulse duration: 1 ns

Intensity range: $2x10^{11}$ - $5x10^{14}$ W/cm^2

Atmosphere: vacuum, unspecified

Spot dimensions: 300 μm and 40-60 μm

Target materials: Aluminum foil

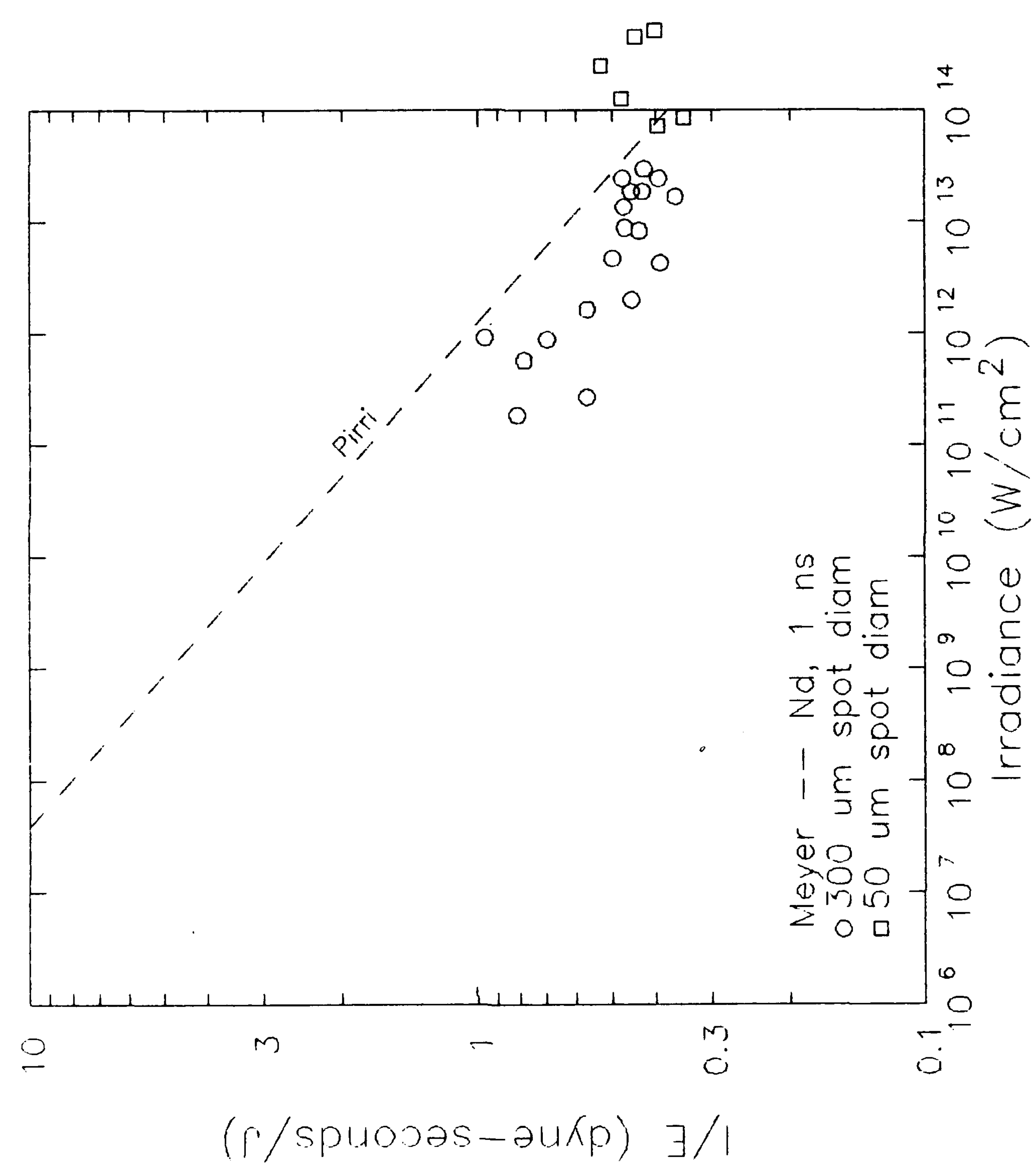
Target dimensions: not specified

Measured quantities: impulse

Measurement technique: Ballistic pendulum

Figure caption: "Transferred momentum versus kinetic energy . . . "

Comments: These 1.06 μm data are in good agreement with other impulse data and with the predictions of the Pirri model. This group also obtained tripled-Nd data, readily compared to the XeF data in this compilation. Those data are not at all in good agreement with other data and the model prediction.



Meyer -- Nd, 1 ns
o 300 um spot diam
□ 50 um spot diam
Pirri
I/E (dyne-seconds/J)
Irradiance (W/cm²)
10
3
1
0.3
0.1
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴

Reference # : ROSEN

Authors : C.J. Rollins, D.I. Rosen, and D.C. Rossi

Citation: Proceedings, Laser Effects and Target Response Meeting (U), Don Moffett ed., Kaman Tempo, Alexandria VA (1 Dec 1985)

Institution: Physical Sciences Inc., Andover MA

Experimental Conditions:

Laser: Nd:glass (KMS Fusion "Chroma")

Wavelength: 1.05 μm

Pulse energy: 1 kJ

Pulse duration: 0.20 - 2.5 μs

Intensity range: $3x10^8$ - $1x10^{11}$ W/cm^2

Atmosphere: vacuum, < 0.1 μbar

Spot dimensions: 0.3, 0.6, 1.2, 1.8 cm diameter

Target materials: Aluminum, S-glass epoxy

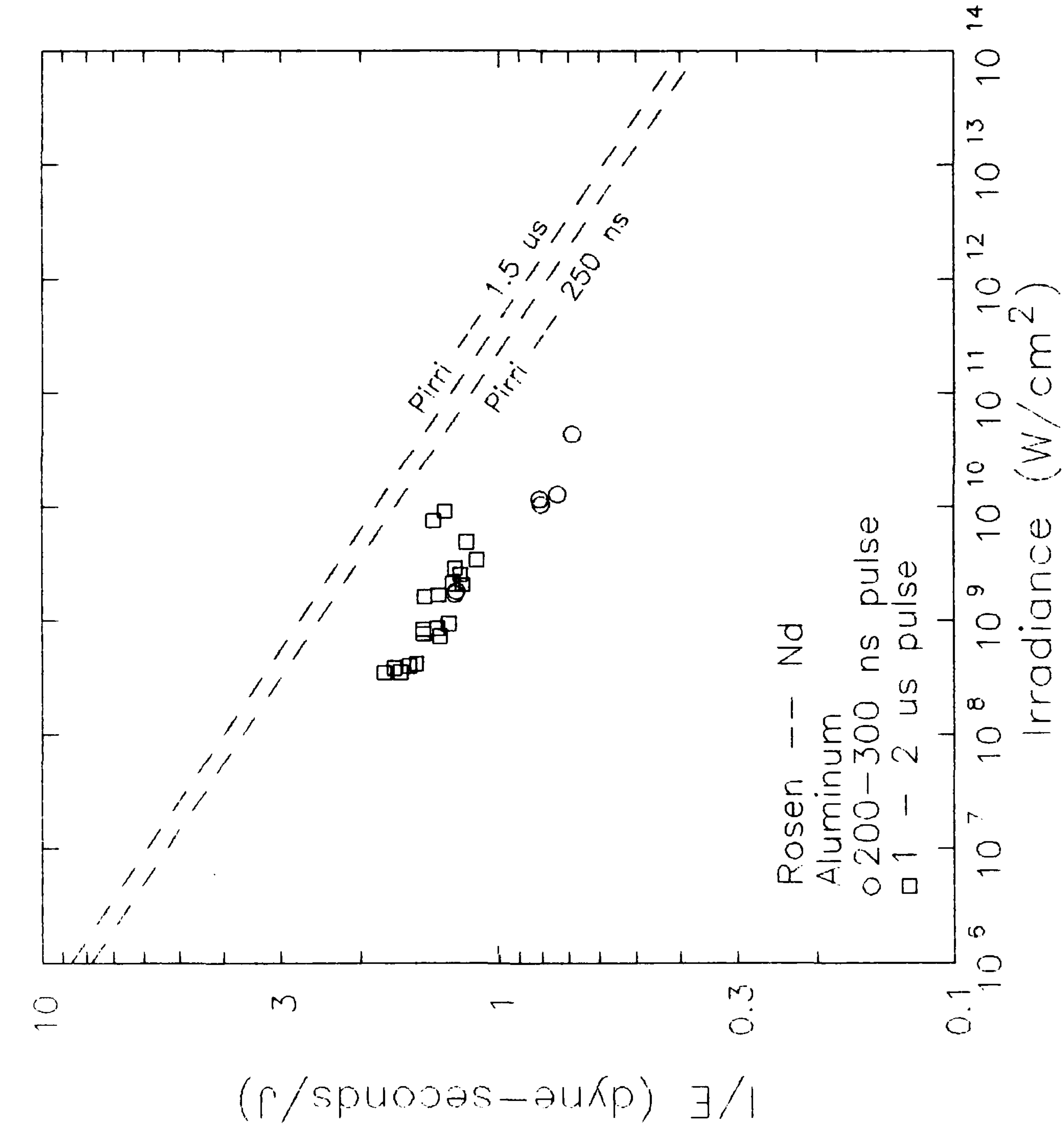
Target dimensions: not specified

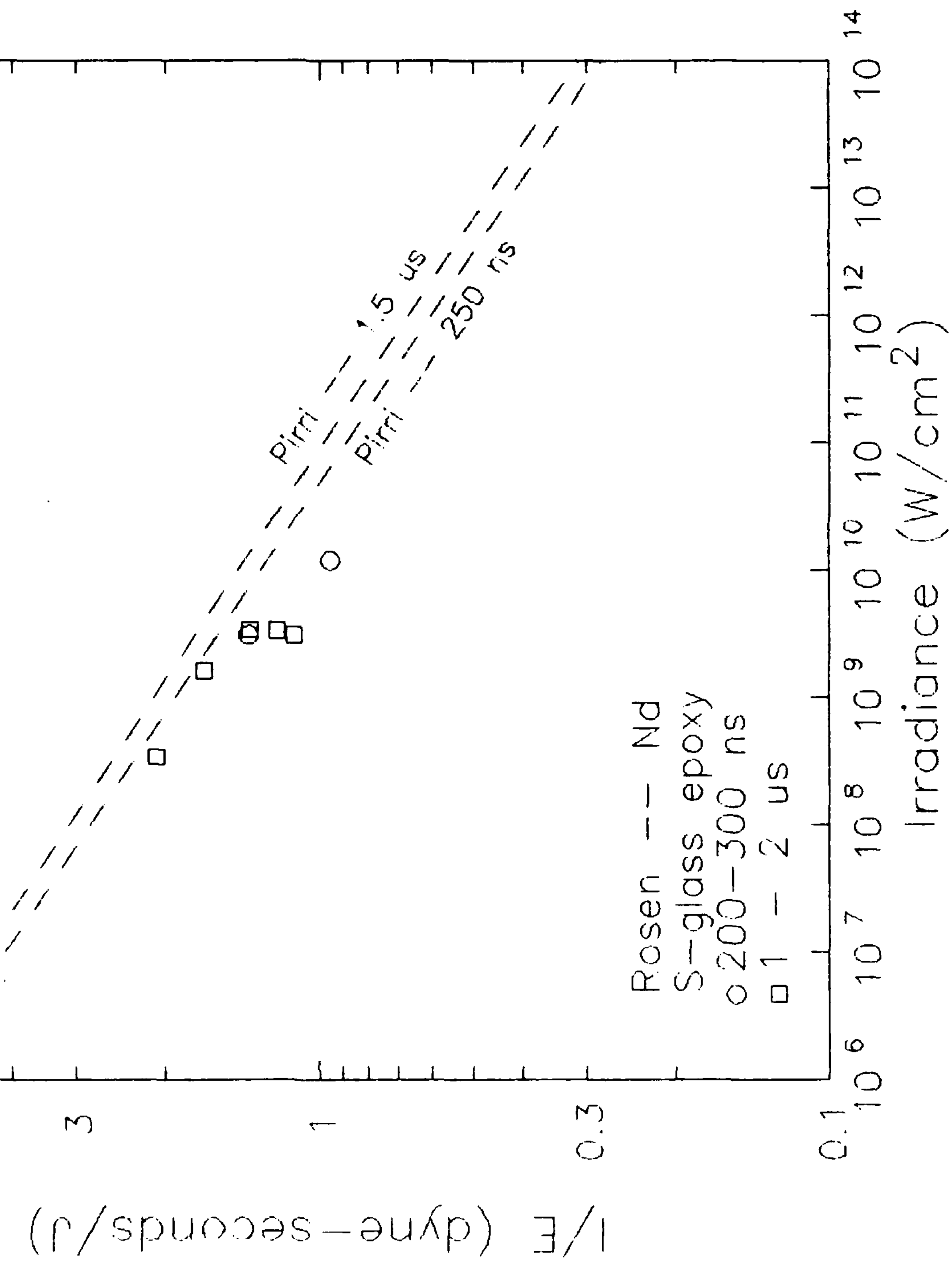
Measured quantities: impulse

Measurement technique: cantilevered beam with strain gauges

Figure caption: "Impulse data for Aluminum"; "Impulse data for S-glass epoxy"

Comments: This work was intended to explore the dependence of impulse coupling on the dimensionality of the interaction. The longer pulse, for which the interaction is two-dimensional, was expected to yield higher coupling than would the shorter pulse, due to improved plasma radial clearing. The aluminum data suggest that this is the case, though the result is hardly conclusive. The Pirri model, which assumes highly two-dimensional conditions, predicts higher coupling for the longer pulse, due to the smaller spot radius for given pulse energy and irradiance. The difference is smaller than the scatter in the experimental data. In short, the conclusion is problematical; compare data by Walters at Battelle, for which high coupling was observed with very short pulses and spot diameters comparable to these.


Rosen -- Nd
Aluminum
○ 200-300 ns pulse
□ 1 - 2 us pulse
Pirri 1.5 us
Pirri 250 ns
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm^2)
10^5
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}


Rosen -- Nd
S-glass epoxy
○ 200-300 ns
□ 1 - 2 us
Pirri -- 1.5 us
Pirri -- 250 ns
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm^2)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

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Reference # : B8

Authors : David W. Gregg and Scott J. Thomas

Citation: "Momentum transfer produced by focused laser giant pulses", J. Appl. Phys. 37, 2787-2789 (1966)

Institution: Lawrence Laboratory, Livermore CA

Experimental Conditions:

Laser: Q-switched ruby

Wavelength: 0.69 μm

Pulse energy: 1.5 J

Pulse duration: 7.5 ns fwhm

Intensity range: 1×10^{8} - 3×10^{10} W/cm^2

Atmosphere: 10^{-5} Torr vacuum

Spot dimensions: 3.4×10^{-3} and 2.9×10^{-2} cm^2

Target materials: beryllium, graphite, aluminum, zinc, silver, tungsten

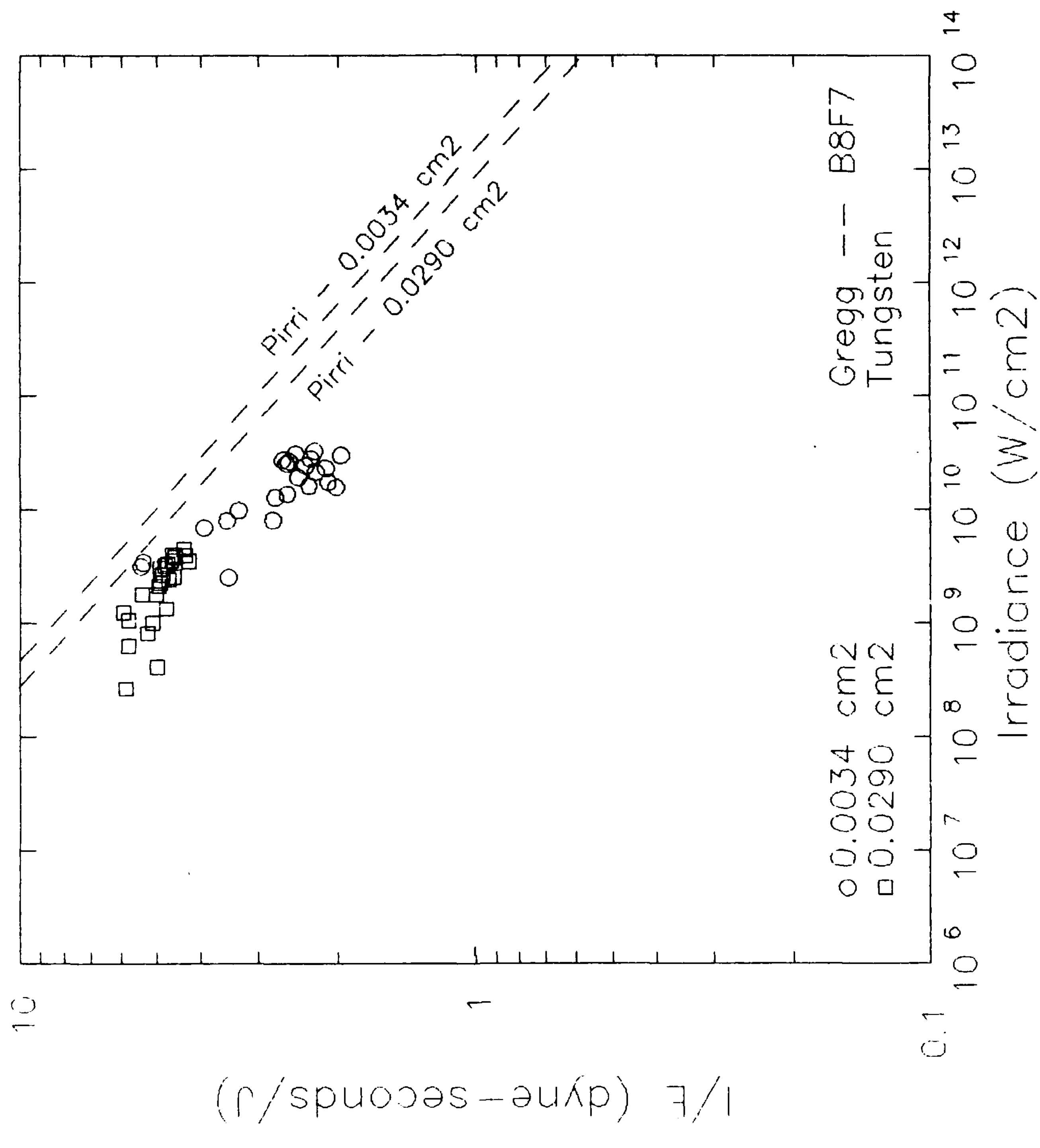
Target dimensions: 1 cm diam sphere

Measured quantities: total impulse

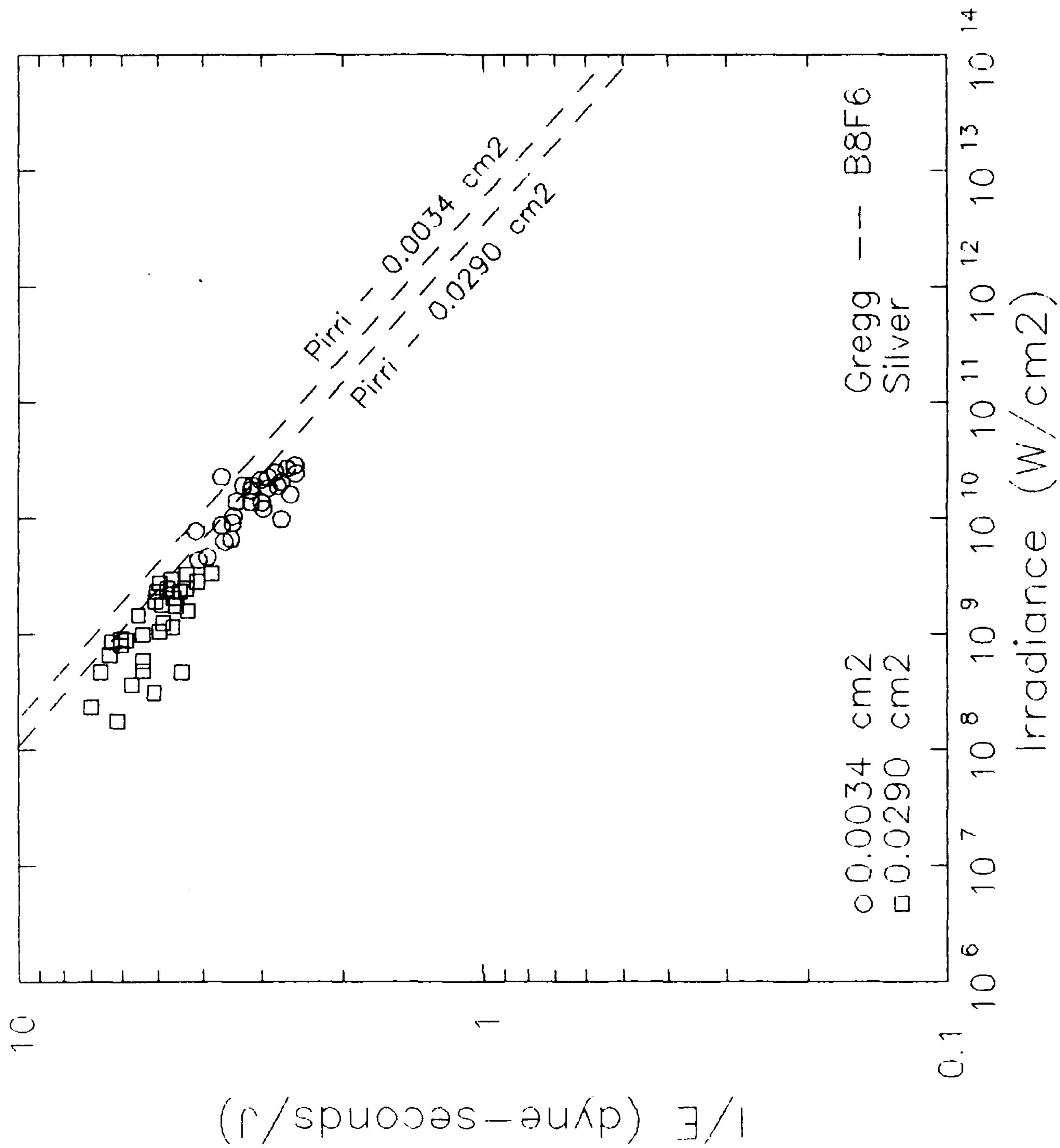
Measurement technique(s): pendulum

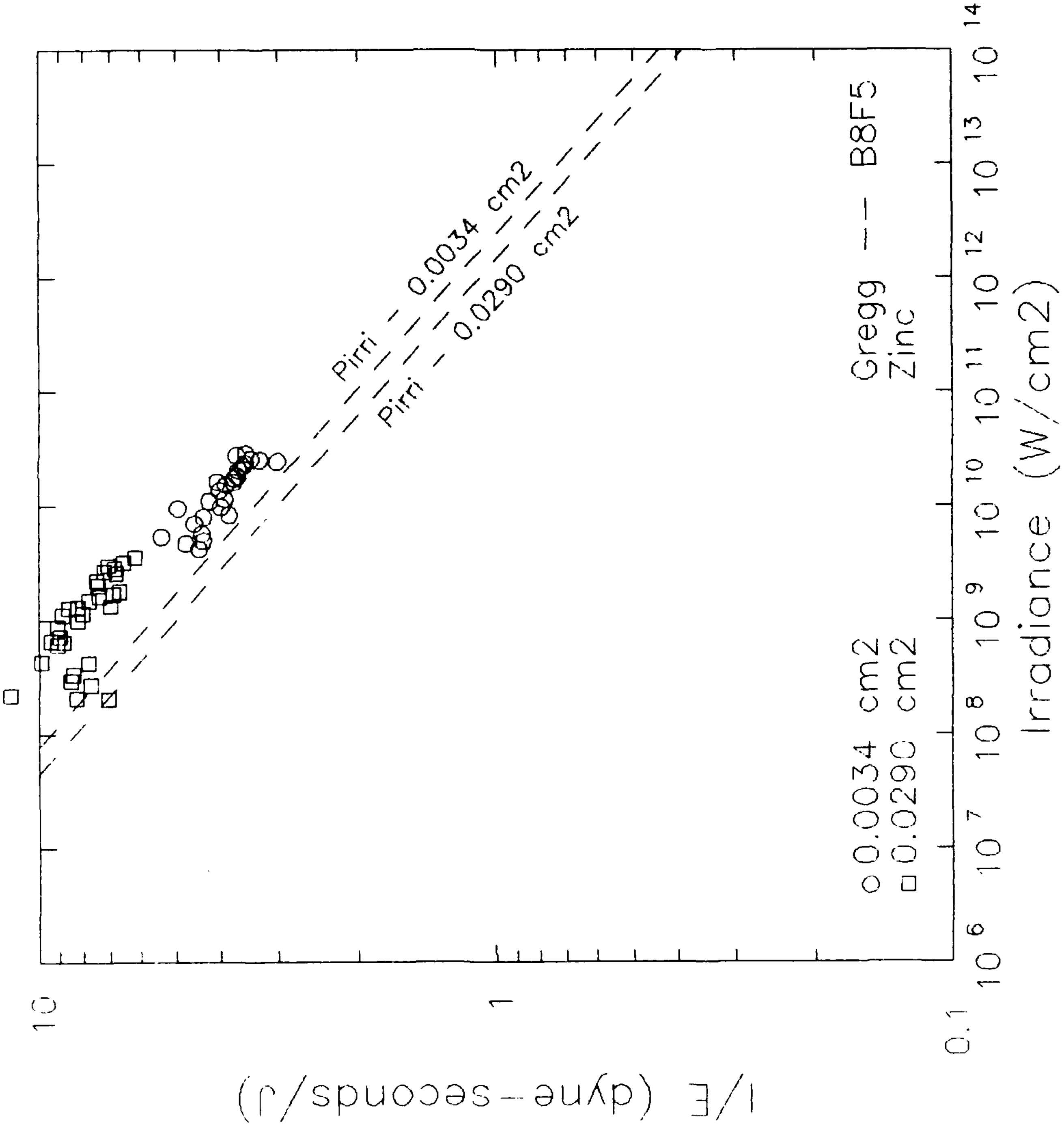
Figure caption: "Momentum transfer to [the specific metal] by laser giant pulse."

Comments: These are among the earliest vacuum-impulse data. The laser pulse is short, and the laser spot dimensions extremely small, so extrapolation to large-area, microsecond-pulse interactions seems unreliable. The Pirri vacuum model works fairly well at describing the impulse delivery, despite its severe approximations.

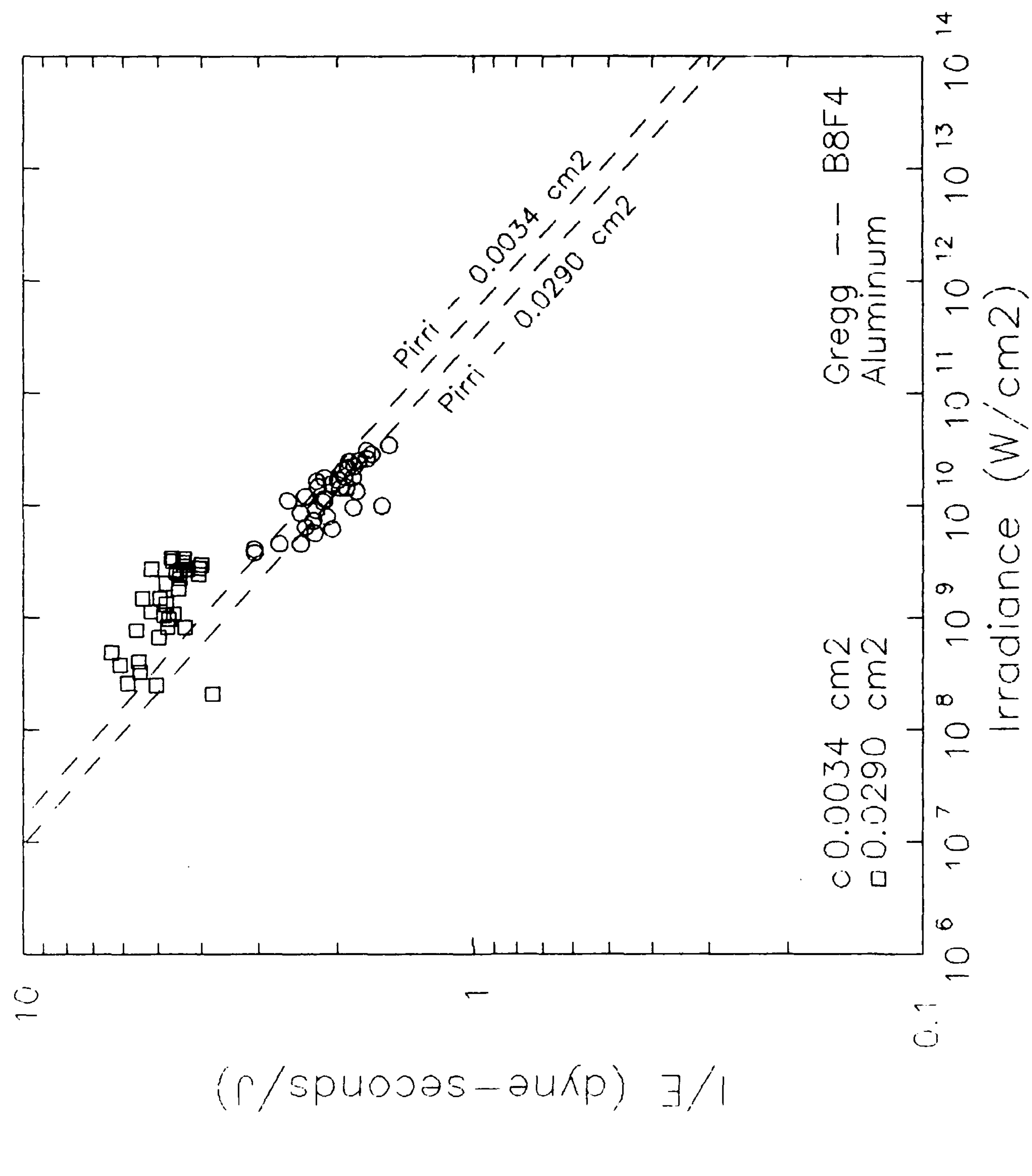


Gregg --- B8F7
Tungsten
○ 0.0034 cm2
□ 0.0290 cm2
Pirri - 0.0034 cm2
Pirri - 0.0290 cm2
Irradiance (W/cm2)
I/E (dyne-seconds/J)
10
1
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

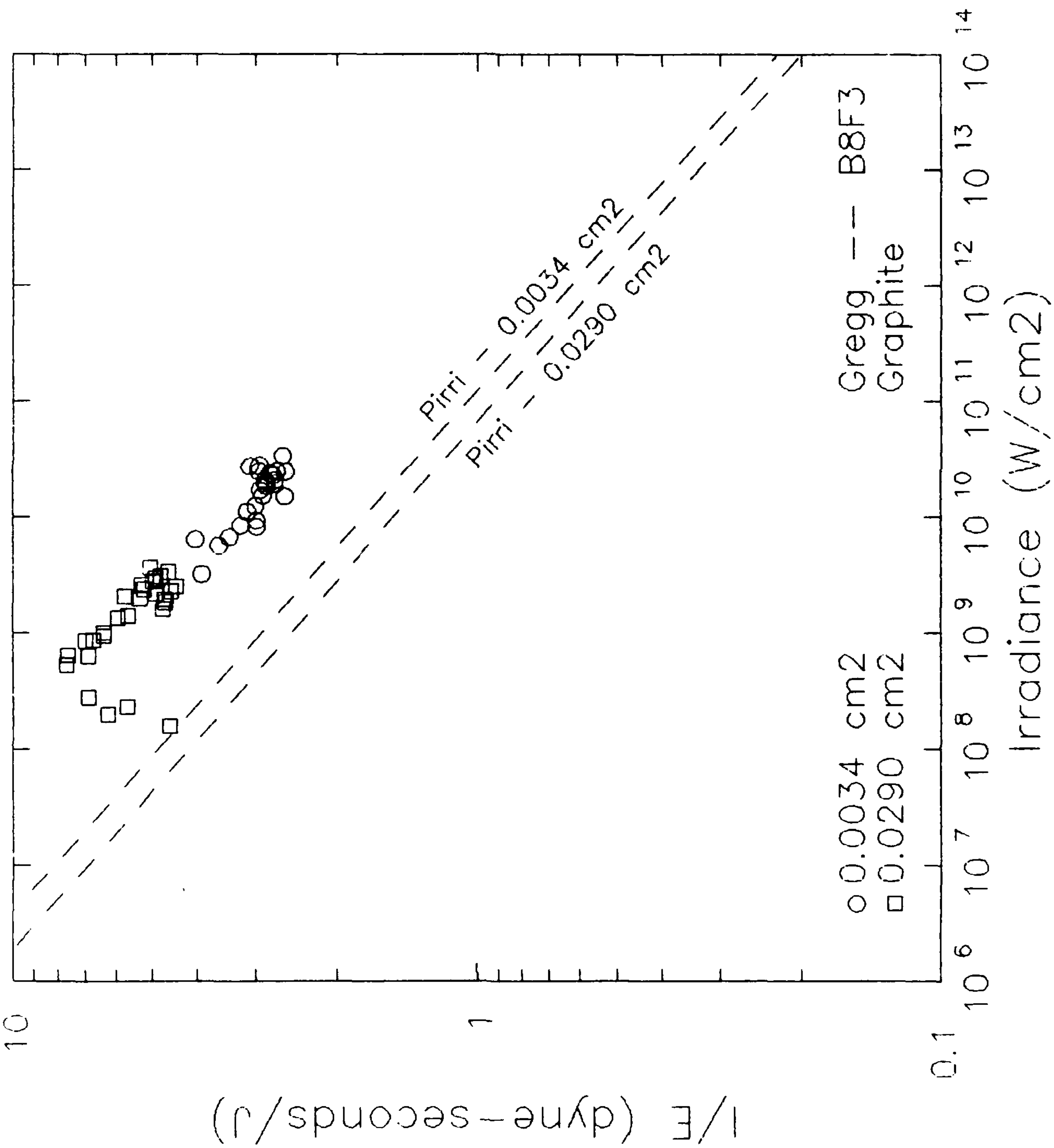

Pirri -- 0.0034 cm2
Pirri -- 0.0290 cm2
Gregg -- B8F6
Silver
○ 0.0034 cm2
□ 0.0290 cm2
Irradiance (W/cm2)
I/E (dyne-seconds/J)
10
1
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}



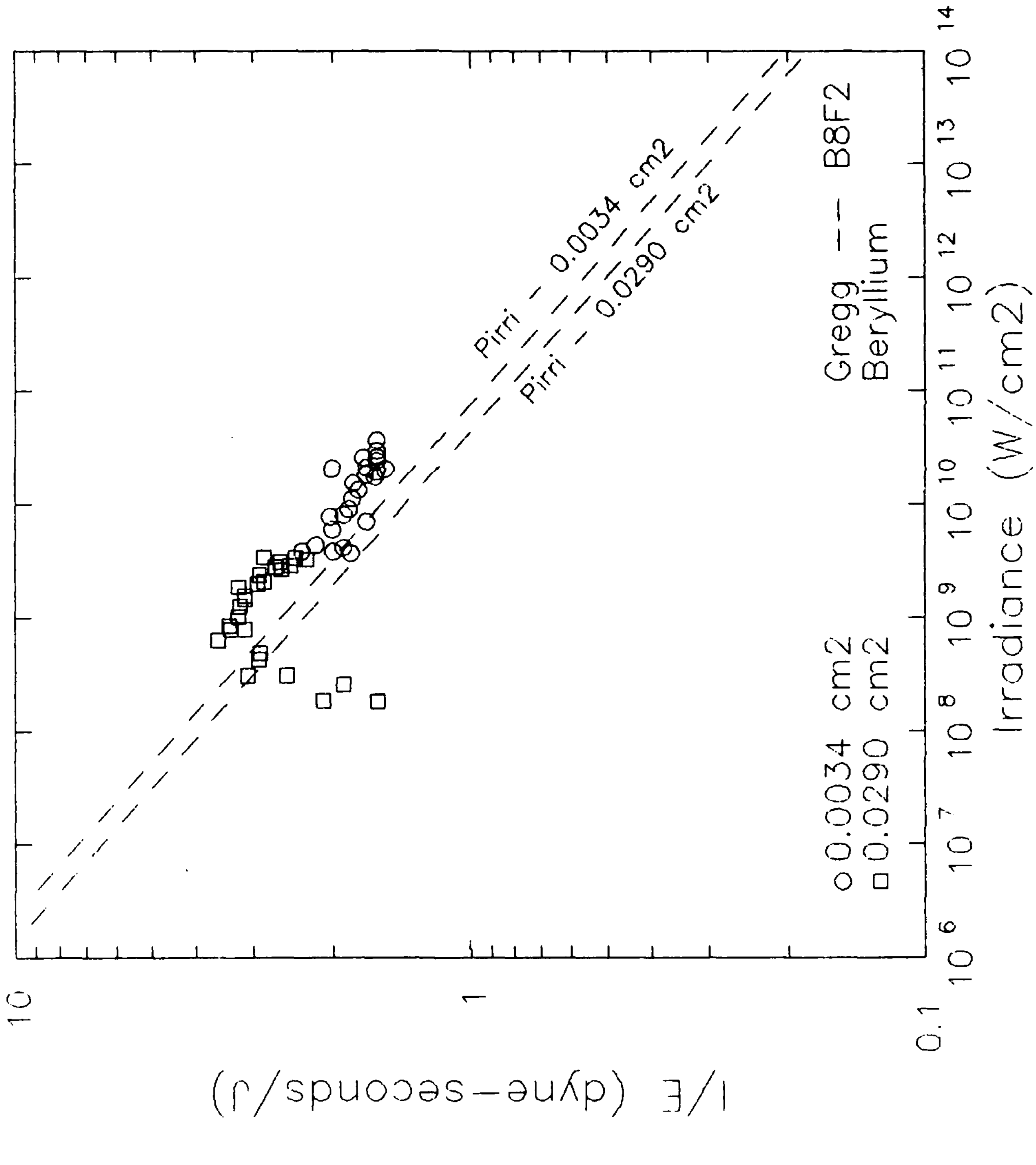
I/E (dyne-seconds/J)
Irradiance (W/cm2)
10
1
0.1
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14
Pirri - 0.0034 cm2
Pirri - 0.0290 cm2
Gregg -- B8F5
Zinc
o 0.0034 cm2
□ 0.0290 cm2



Gregg -- B8F4
Aluminum
Pirri - 0.0034 cm2
Pirri - 0.0290 cm2
o 0.0034 cm2
□ 0.0290 cm2
Irradiance (W/cm2)
I/E (dyne-seconds/J)
10
1
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}



I/E (dyne-seconds/J)
Irradiance (W/cm2)
10
1
0.1
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
Pirri - 0.0034 cm2
Pirri - 0.0290 cm2
○ 0.0034 cm2
□ 0.0290 cm2
Gregg --- B8F3
Graphite



Gregg — B8F2
Beryllium
○ 0.0034 cm2
□ 0.0290 cm2
Pirri - 0.0034 cm2
Pirri - 0.0290 cm2
Irradiance (W/cm2)
I/E (dyne-seconds/J)

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Reference # : B38F4

Authors : C. Duzy, J.A. Woodroffe, J.C. Hsia, and A. Ballantyne

Citation: "Interaction of a pulsed XeF laser with an aluminum surface", Appl. Phys. Lett. 37, 542-544 (1980)

Institution: Avco-Everett Research Laboratory, Everett MA

Experimental Conditions:

Laser: e-beam XeF

Wavelength: 0.35 μm

Pulse energy: 0.8 - 2.0 J

Pulse duration: 0.5-1.4 μs

Intensity range: $4x10^6$ - $3x10^7$ W/cm^2

Atmosphere: vacuum, unspecified

Spot dimensions: variable, 0.22 - 0.87 cm diameter

Target materials: 2024-T3 aluminum

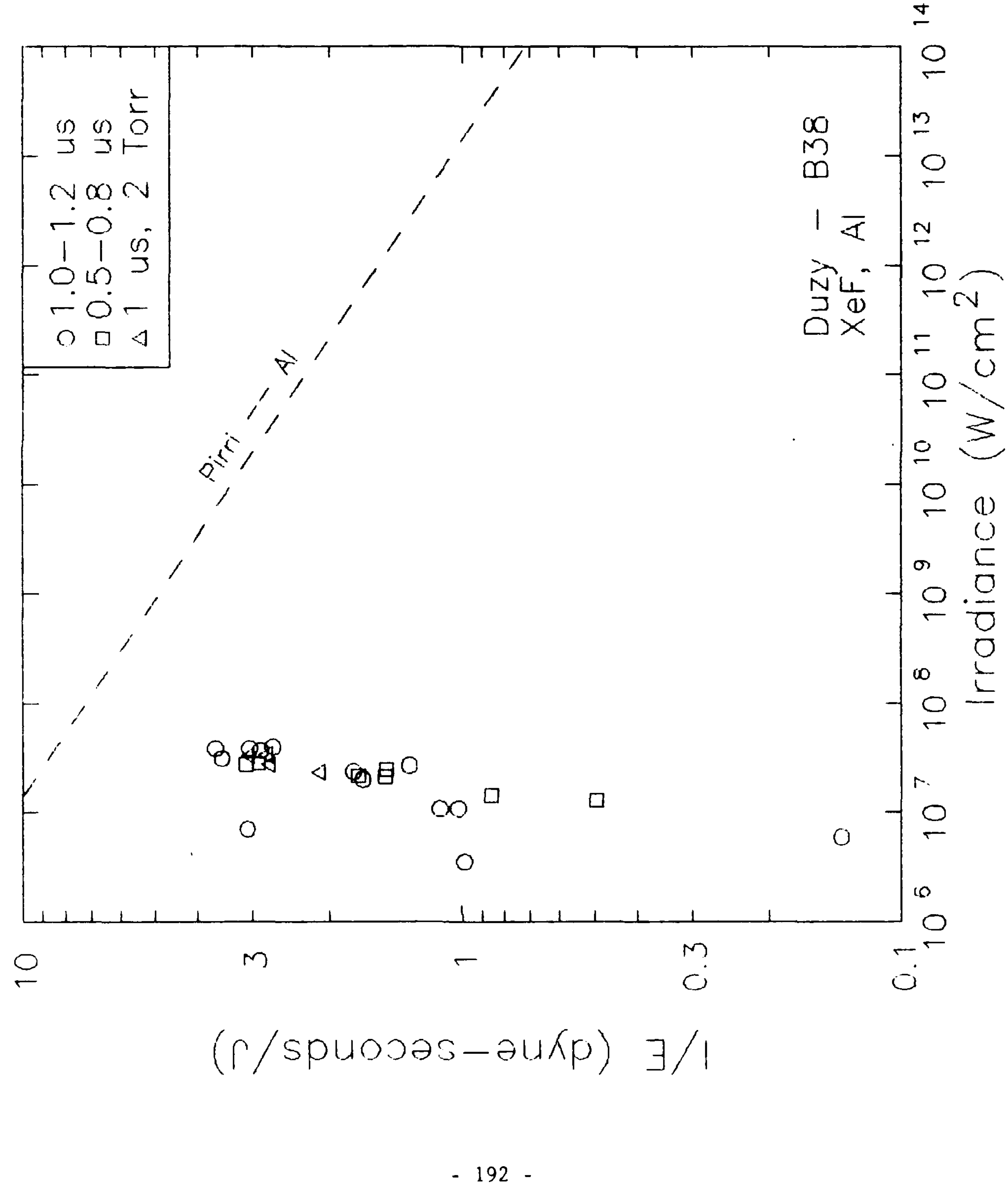
Target dimensions: not specified

Measured quantities: impulse

Measurement technique: Pendulum

Figure caption: "Impulse coupling coefficients for XeF to an aluminum surface as a function of incident fluence. Energies of 0.8 - 2.0 J were used."

Comments: These data, taken at low irradiance with a modest laser, pertain to a transparent-vapor, target-ablation regime, below the regime of a fully developed plasma. The results will be strongly dependent on material thermal coupling and vaporization details, and cannot be extrapolated to higher irradiances.



1.0–1.2 us
0.5–0.8 us
1 us, 2 Torr
Pirri — Al
Duzy – B38
XeF, Al
Irradiance (W/cm²)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1

Reference # : A07

Authors : D.I. Rosen, D.E. Hastings, and G.M. Weyl

Citation: "Coupling of pulsed 0.35-μm laser radiation to titanium alloys", J. Appl. Phys. 53, 5882-5890 (1982).

Institution: Physical Sciences Inc., Andover MA

Experimental Conditions:
- Laser: e-beam XeF (Maxwell "Maximer")
  - Wavelength: 0.35 μm
  - Pulse energy: 5 J
  - Pulse duration: 0.6 μs
- Intensity range: 1×10^7 - 1×10^8 W/cm^2
- Atmosphere: vacuum, 0.1 μbar

Spot dimensions: 0.04 - 4 cm^2 area

Target material: titanium 6Al-4V alloy

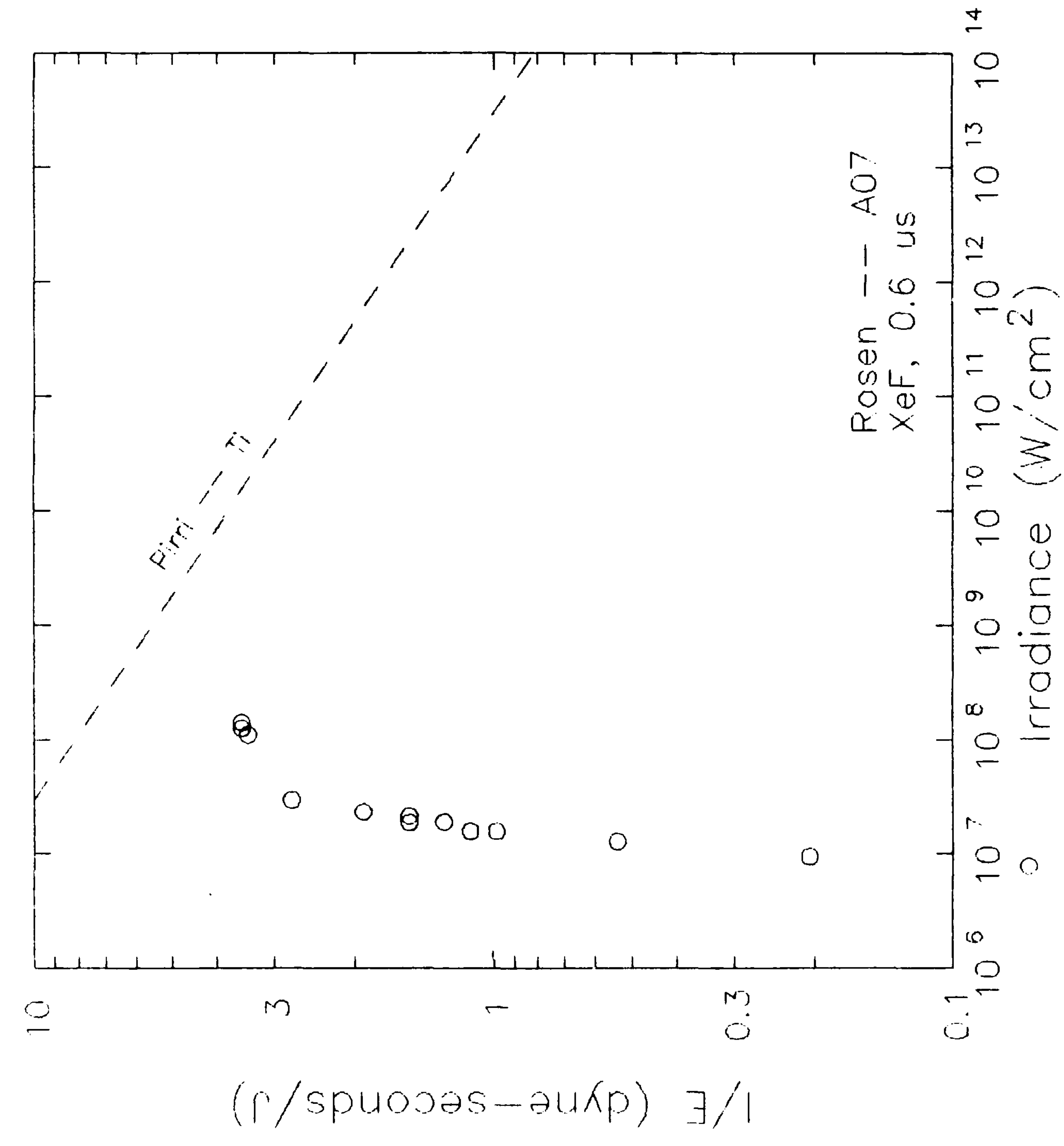
Target dimensions: not specified

Measured quantities: impulse

Measurement technique: ballistic pendulum

Figure caption: "Theory/data comparison of the vacuum impulse coupling coefficient to a Ti6Al4V target. . ."

Comments: This set of impulse data displays the near-threshold behavior of impulse generation. The coupling values lie far below the Pirri values corresponding to a fully developed plasma.


Rosen —— A07
XeF, 0.6 us
Pirri —— Ti
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

Reference # : B11

Authors : D.I. Rosen, J. Mitteldorf, G. Kothandaraman, A.N. Pirri, and E.R. Pugh

Citation: "Coupling of pulsed 0.35-μm laser radiation to aluminum alloys", J. Appl. Phys. 53, 3190-3200 (1982).

Institution: Physical Sciences Inc., Andover MA

Experimental Conditions:

Laser: e-beam XeF (Maxwell "Maximer")
Wavelength: 0.35 μm
Pulse energy: 3 J
Pulse duration: 0.5 μs
Intensity range: 1×10^{7} - 1×10^{8} W/cm^2
Atmosphere: vacuum, 0.1 μbar

Spot dimensions: 0.2 - 0.4 cm diameter

Target material: 2024 aluminum alloy

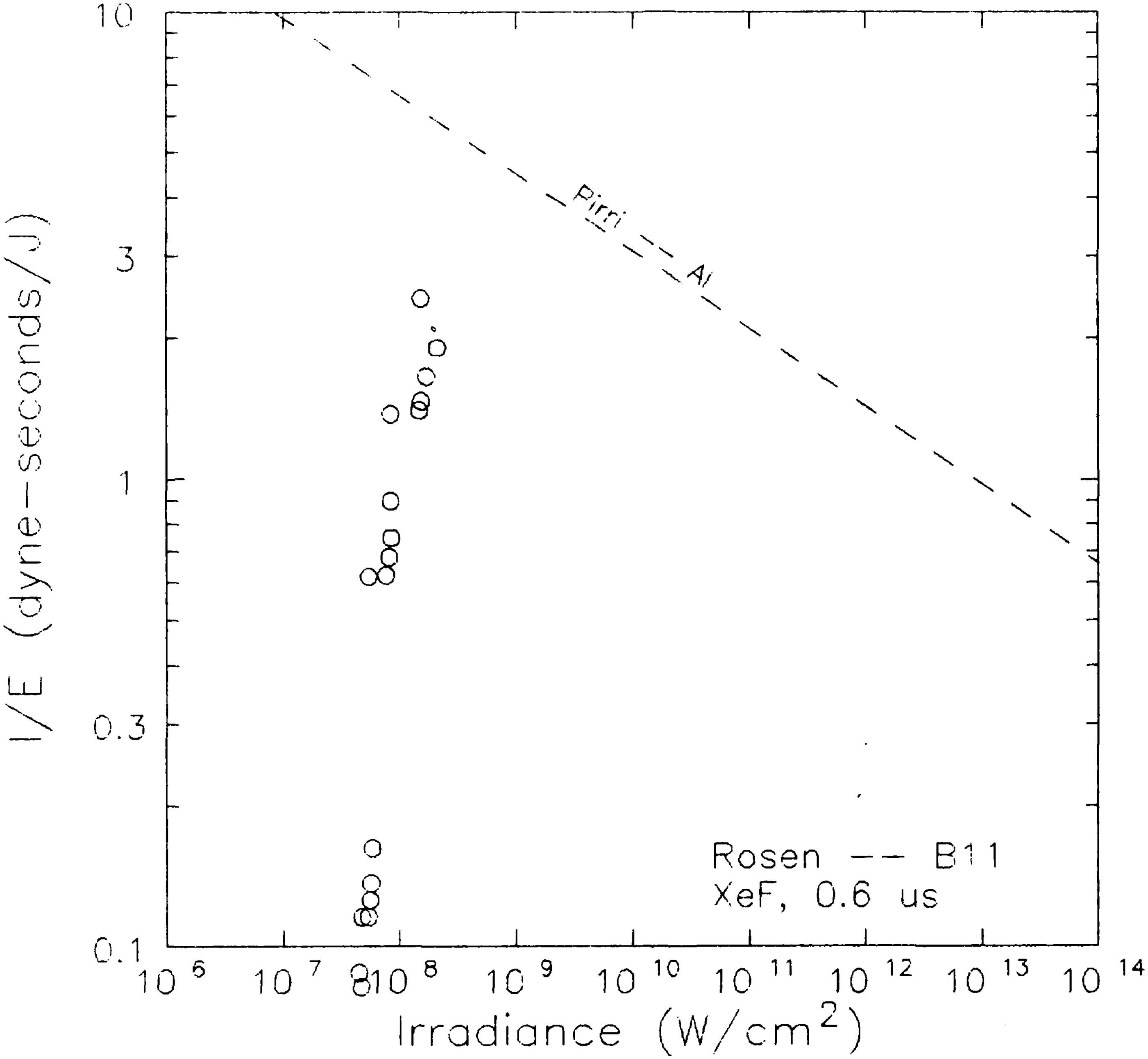
Target dimensions: not specified

Measured quantities: impulse

Measurement technique: ballistic pendulum

Figure caption: "Impulse coupling coefficient data for Al 2024 targets (polished), 0.5 μs, vacuum."

Comments: This set of impulse data, like Rosen's set on titanium (A07), displays the near-threshold behavior of impulse generation. The coupling values lie far below the Pirri values corresponding to a fully developed plasma.


I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
Irradiance (W/cm2)
Pirri --- Al
Rosen --- B11
XeF, 0.6 us

Reference # : MEYER2

Authors : B. Meyer and G. Thiell

Citation: "Experimental scaling laws for ablation parameters in plane target-laser interaction with 1.06 μm and 0.35 μm laser wavelengths", Phys. Fluids 27, 302-311 (1984).

Institution: Commissariat a l'Energie Atomique, Centre d'Etudes de Limeil, Villeneuve-Saint-Georges, France

Experimental Conditions:

Laser: Nd:glass

Wavelength: 0.35 μm

Pulse energy: 35 J

Pulse duration: 1 ns

Intensity range: $7x10^{11}$ - $2x10^{13}$ W/cm²

Atmosphere: vacuum, unspecified

Spot dimensions: 300 μm

Target materials: Aluminum foil

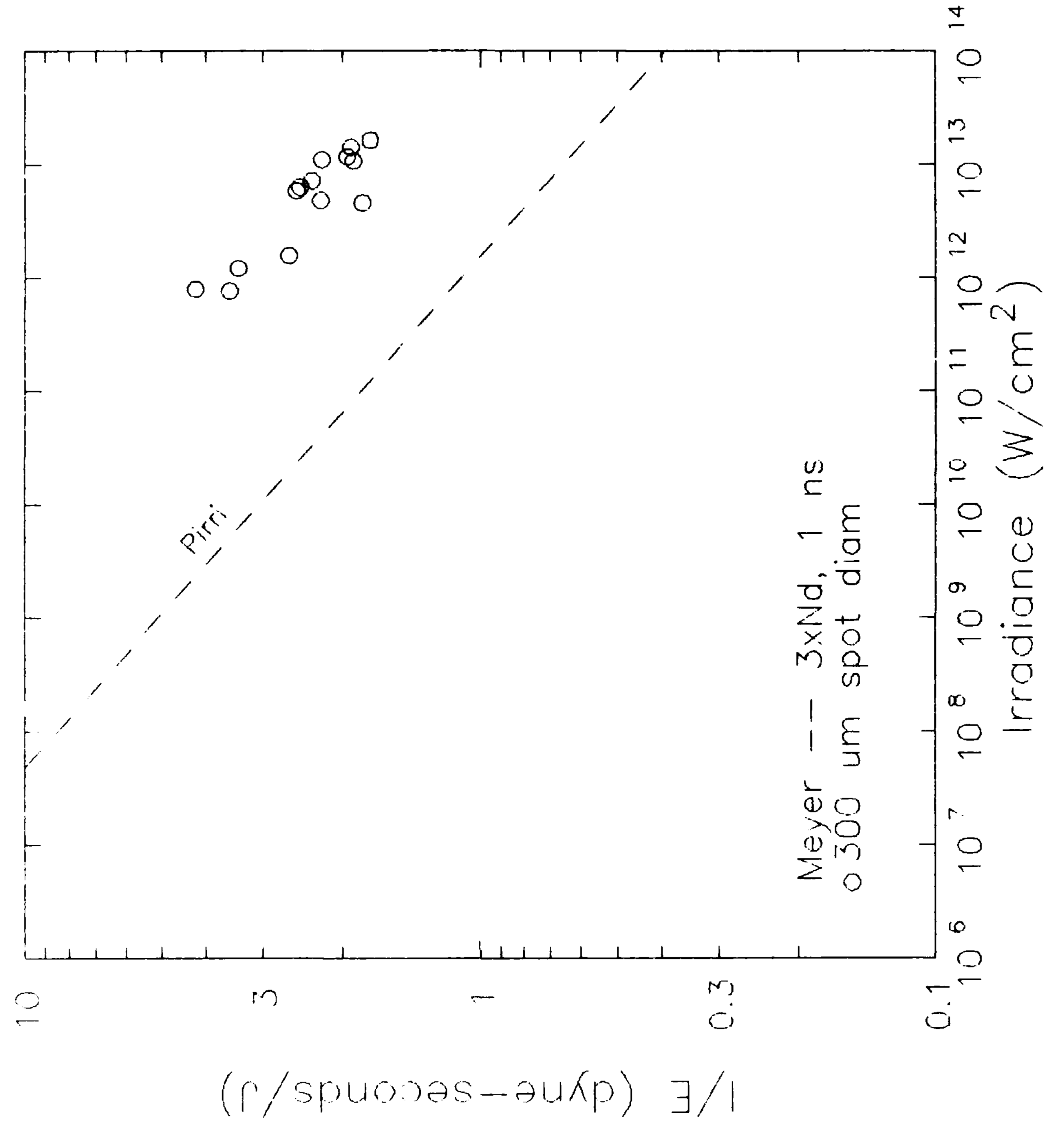
Target dimensions: not specified

Measured quantities: impulse

Measurement technique: Ballistic pendulum

Figure caption: "Transferred momentum versus kinetic energy . . . "

Comments: These 0.35 μm data, which should be directly comparable to XeF impulse data, are substantially higher than would be expected either by comparison with other data (especially 0.25 μm results in the same irradiance range) or with the predictions of the Pirri model. This led Meyer and Thiell to deduce a very strong wavelength dependence to impulse coupling, as wavelength to the -2/3 power, while all other data indicate that the wavelength dependence is even weaker than the -2/9 power predicted by the Pirri model.


Meyer -- 3xNd, 1 ns
○ 300 um spot diam
Pirri
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
0.1
0.3
1
3
10

Reference # : T1

Authors : R.S. Wilson

Citation: "Two-meter laser material response measurements", Maxwell Laboratories report MLR-2320 (25 April 1986)

Institution: Maxwell Laboratories, San Diego CA

Experimental Conditions:

Laser: Maxwell Laboratories 2-meter excimer (XeF)
Wavelength: 0.35 μm
Pulse energy: 75 J
Pulse duration: 1.8 μs
Intensity range: 1×10^8 - 1×10^9 W/cm^2
Atmosphere: vacuum, 0.05 - 5 Torr (70 μbar - 7 mbar)

Spot dimensions: 0.2x0.4 cm

Target materials: Aluminum

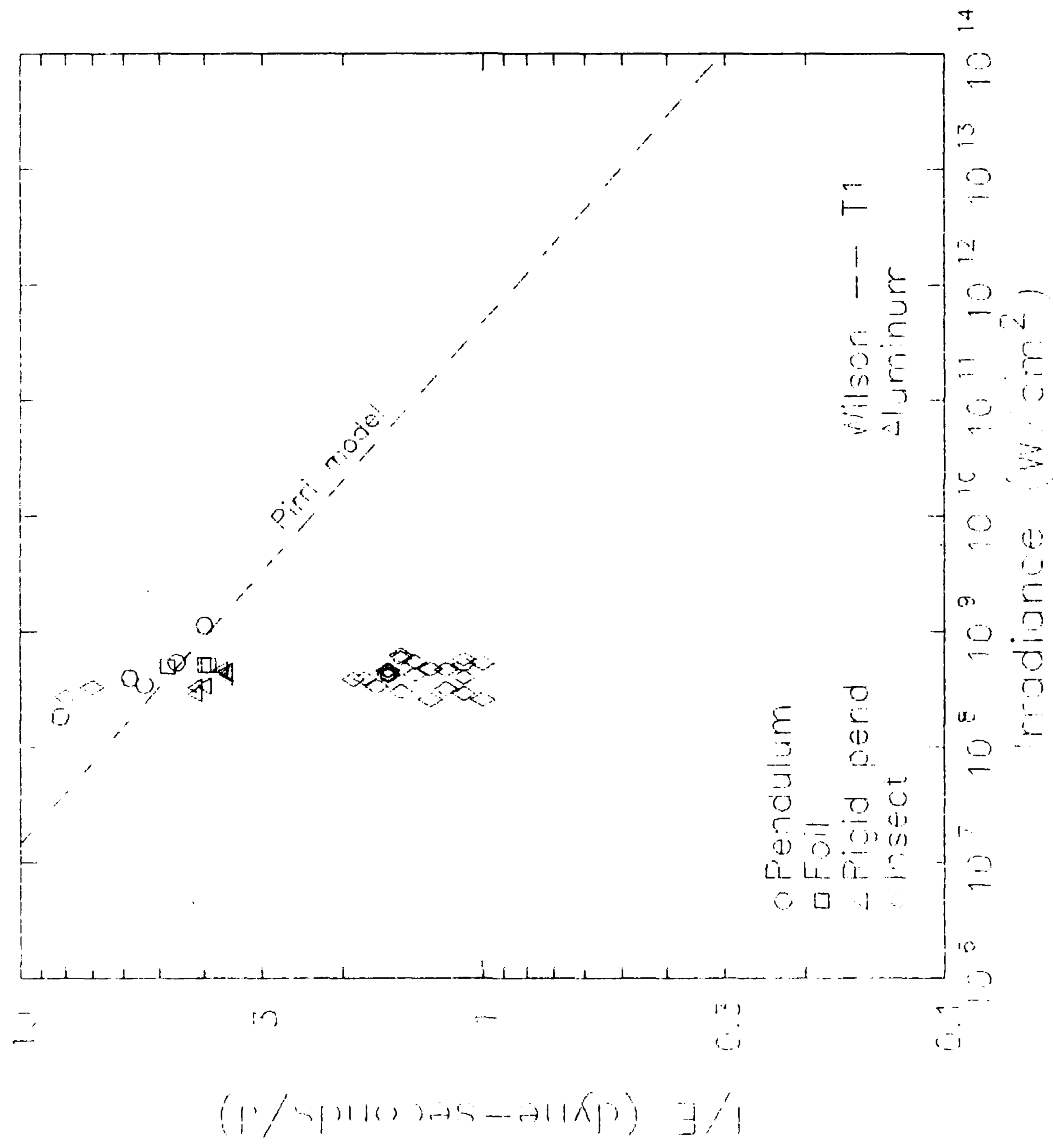
Target dimensions: large compared to laser spot, except for the "insect" device

Measured quantities: impulse

Measurement technique: ballistic pendula in four different configurations. (1) thread-suspension pendulum. (2) Same, with foil target face. (3) Pendulum with rigid hanger suspension to prevent twisting. (4) "Insect" pendulum, an aluminum bar 2x4x50 mm hit on the small face to measure true specific impulse.

Table caption: "Pendulum impulse data." "Impulse data from laser footprint target."

Comments: The measurements with the large-area pendula are consistent with other observations. The impulse pendulum devised to measure impulse within the laser spot alone yielded substantially smaller coupling coefficients. The Pirri model does not allow for impulse delivery outside the laser-irradiated area. It is possible that the fair agreement between the simple model and a great deal of the laser impulse data is fortuitous, the results of most measurements being subject to perturbation by phenomena producing impulse outside the laser spot.



Pendulum
Foil
Rigid pend
Insect
Wilson — T1
Aluminum
Pirri model
Irradiance (W/cm²)
I/E (dyne-seconds/J)

Reference # : T2TB1V

Authors : R.S. Wilson

Citation: "Measurements of material response to excimer laser irradiation", S-Cubed report SSS-R-86-7629 (30 Jan 1986)

Institution: S-Cubed Inc., La Jolla CA

Experimental Conditions:

Laser: Maxwell Laboratories 2-meter excimer (XeF)

Wavelength: 0.35 μm

Pulse energy: 75 J

Pulse duration: 1.8 μs

Intensity range: 1×10^8 - 1×10^9 W/cm^2

Atmosphere: vacuum, 0.05 - 5 Torr (70 μbar - 7 mbar)

Spot dimensions: (a) 0.27x0.135 cm, (b) 0.41x0.205 cm, (c) 0.49x0.245 cm

Target materials: Aluminum, Chemglaze, and S-glass epoxy

Target dimensions: 0.95 cm diam

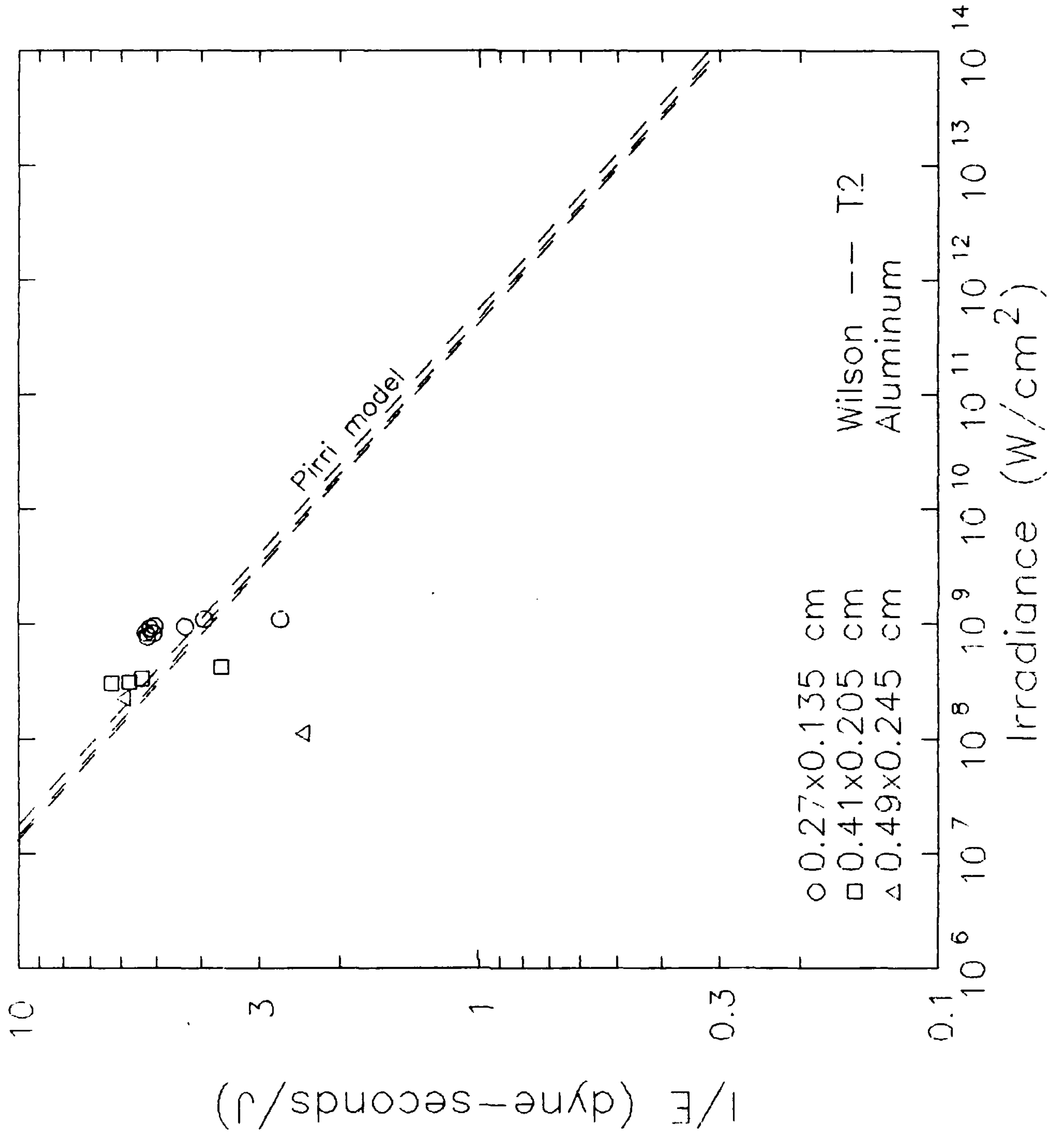
Measured quantities: pressure and total impulse

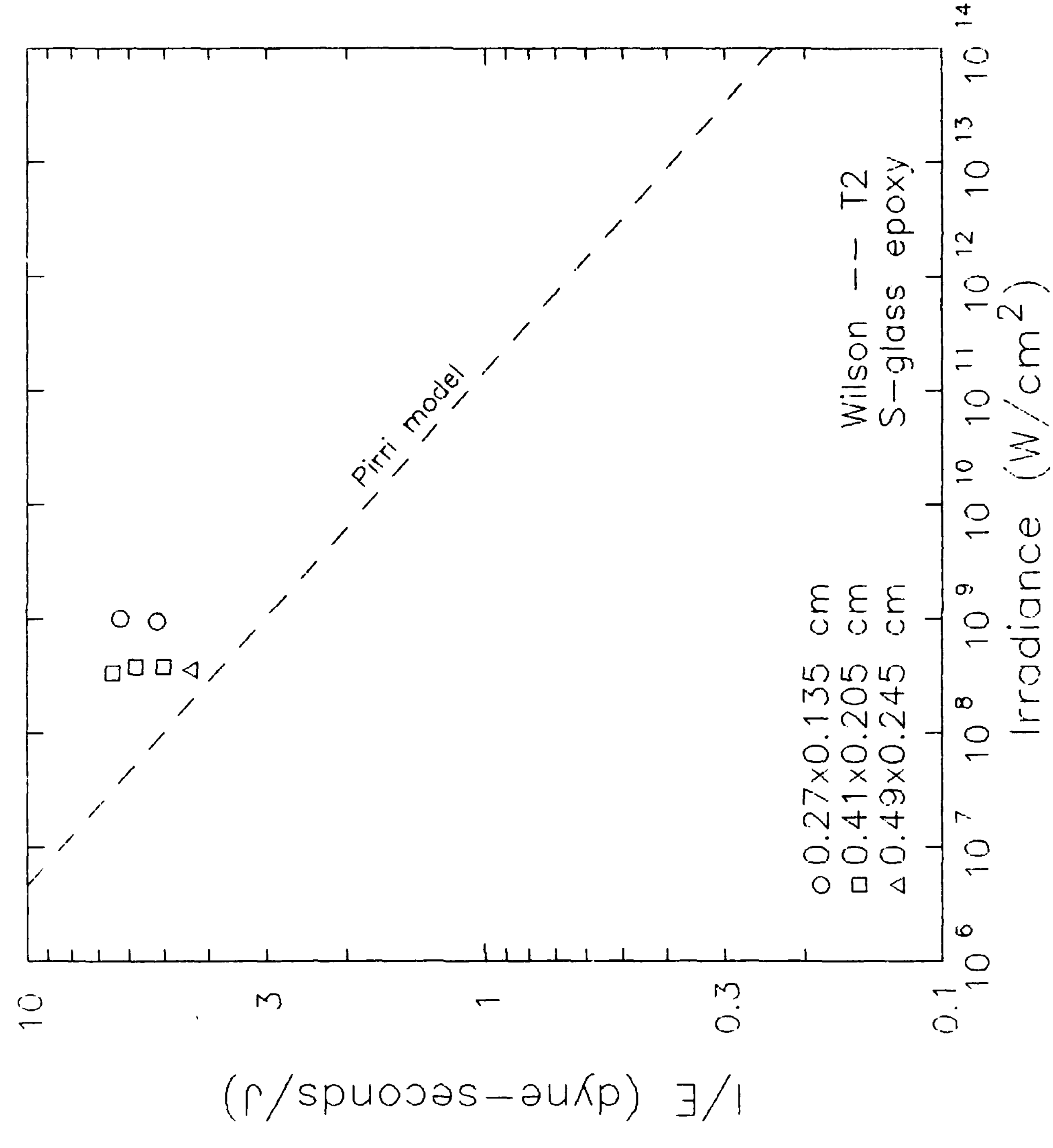
Measurement technique: (a) pressure: ytterbium piezoresistive gauge, (b) impulse: optical velocity transducer behind block suspended on loose membrane

Table caption: "Summary of test results."

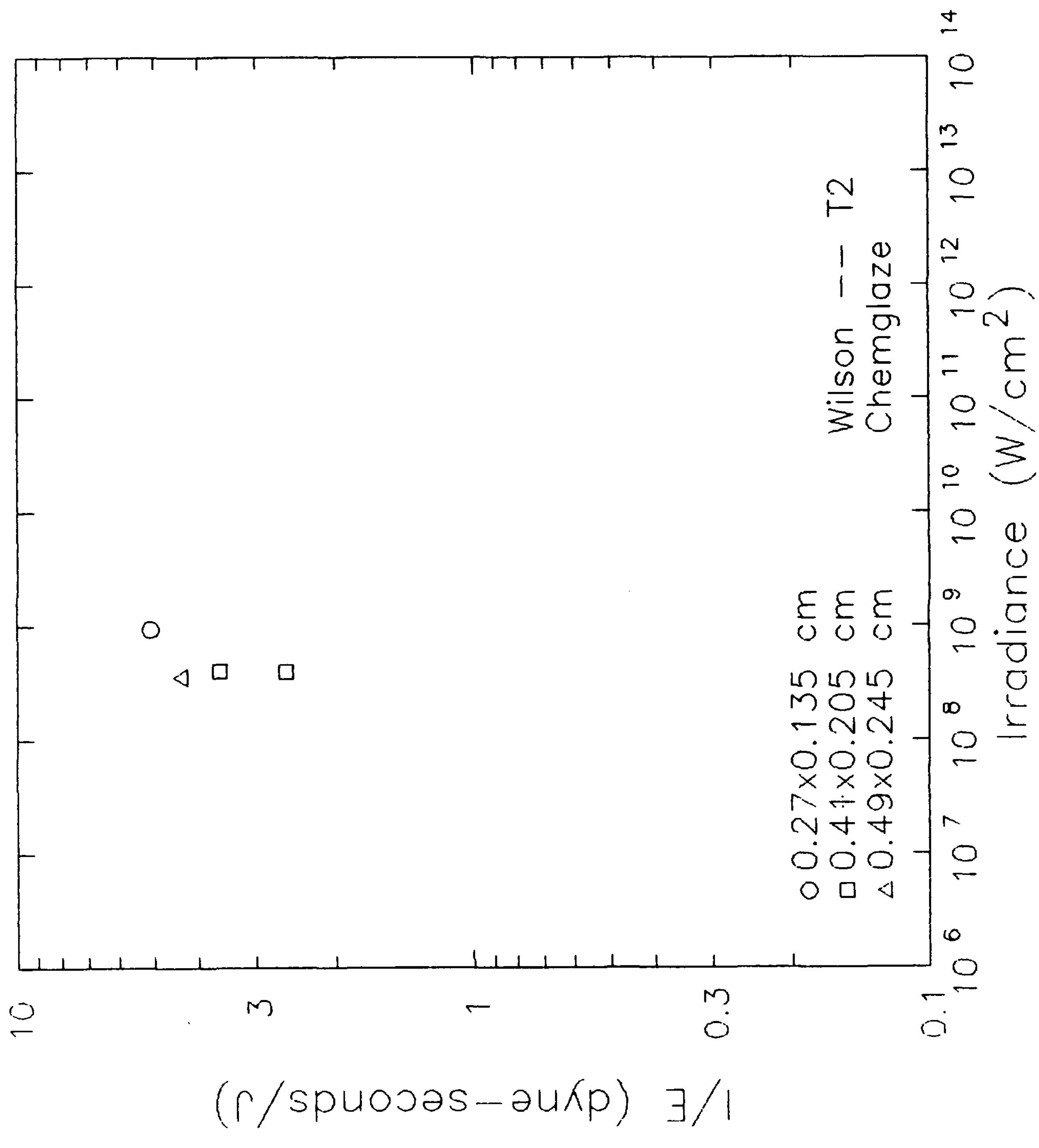
Comments: These impulse coupling values are among the highest ever measured. Identical measurements on the same laser, with nominally the same conditions, yielded values lower by about a factor 2.

The Pirri model values were obtained using the radius of a circle with the same area as the experimental rectangle. For S-glass, an atomic weight of 14 was used, i.e. nitrogen. The other major constituents -- carbon and oxygen -- are not very different. For Chemglaze, not enough information was available on the composition of this material to attempt a model calculation; however, a line similar to those for aluminum and nitrogen is expected.


Wilson -- T2
Aluminum
○ 0.27×0.135 cm
□ 0.41×0.205 cm
△ 0.49×0.245 cm
Pirri model
Irradiance (W/cm²)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴



Wilson — T2
S-glass epoxy
Pirri model
○ 0.27×0.135 cm
□ 0.41×0.205 cm
△ 0.49×0.245 cm
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}


Wilson — T2
Chemglaze
○ 0.27x0.135 cm
□ 0.41x0.205 cm
△ 0.49x0.245 cm
Irradiance (W/cm²)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴

Reference # : T6

Authors : A.L. Augustoni, P.G. Ermer, R.T. Heckler, G.R. Kuwashima, J.A. McKay, and R.R. Rudder

Citation: "The interaction of high energy single pulse XeF laser radiation with solid targets", AFWL-TR-85-126 (June 1986)

Institution: Air Force Weapons Laboratory, Albuquerque NM

Experimental Conditions:
Laser: e-beam XeF (Avco-Everett "Scale-up")
Wavelength: 0.35 μm
Pulse energy: 670 J
Pulse duration: 1.5 μs
Intensity range: 1×10^{8} - 1×10^{11} W/cm^2
Atmosphere: vacuum, 0.03 Torr (40 μbars)

Spot dimensions: 0.4 to 1.8 cm diameter, plus a few shots at about 0.1 cm diameter

Target materials: Aluminum and s-glass epoxy

Target dimensions: (A) The targets for the beam-encoder impulse measurements were only very slightly larger than the laser spot, in an effort to measure the true specific impulse. The target diameters were 2.2 cm (1.8 cm laser spots), 1.45 cm (1.0 cm laser), and 1.0 cm (0.6 cm laser).

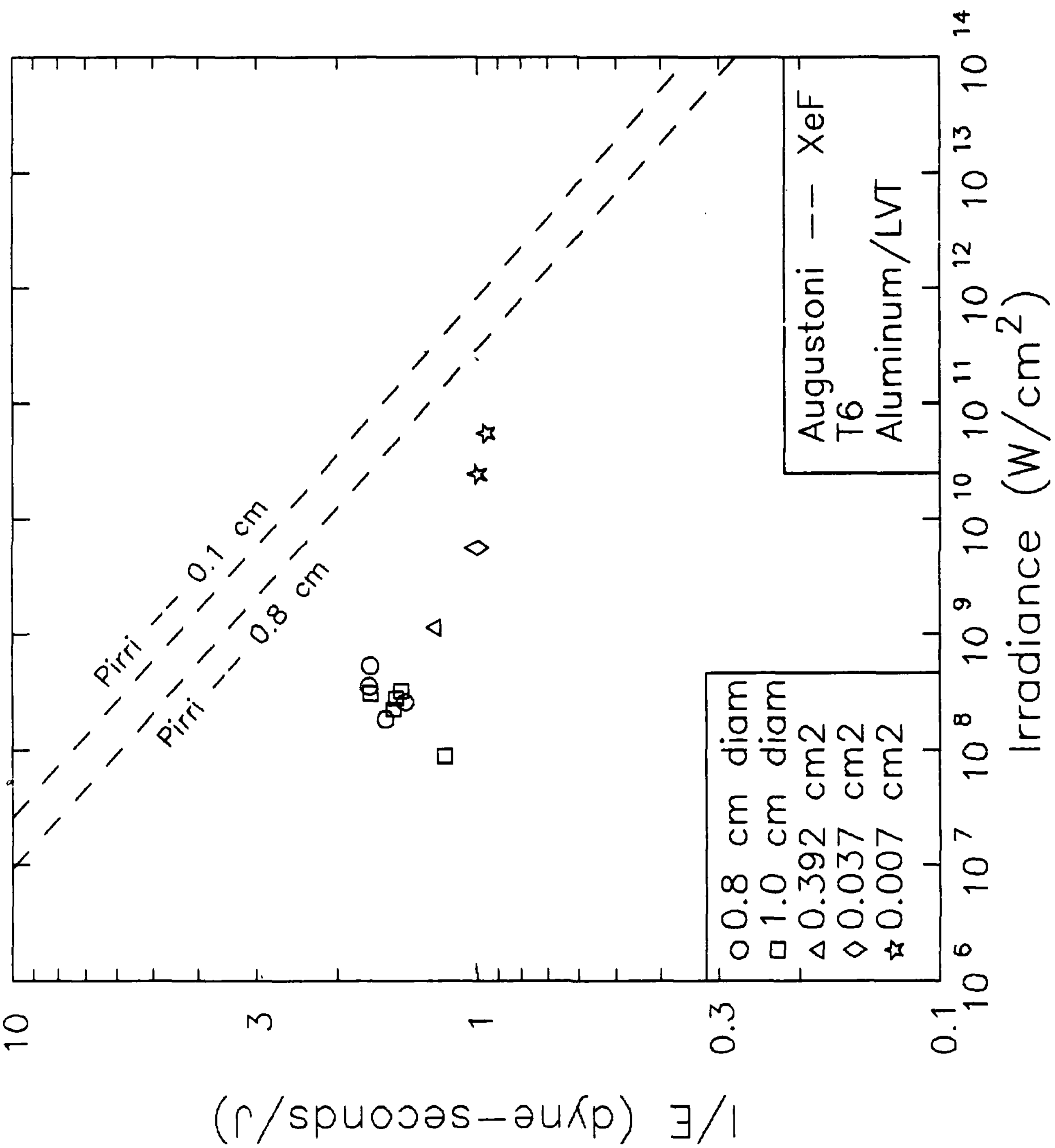
(B) The target diameters for the LVT-gauge runs ranged from 0.6 to 3.0 cm diameter. Frequently the gauge diameter was only slightly larger than the laser spot, but several measurements employed large-diameter targets in an effort to quantify impulse delivery outside the laser spot. No significant difference between large-target and small-target measurements was observed.

Measured quantities: impulse

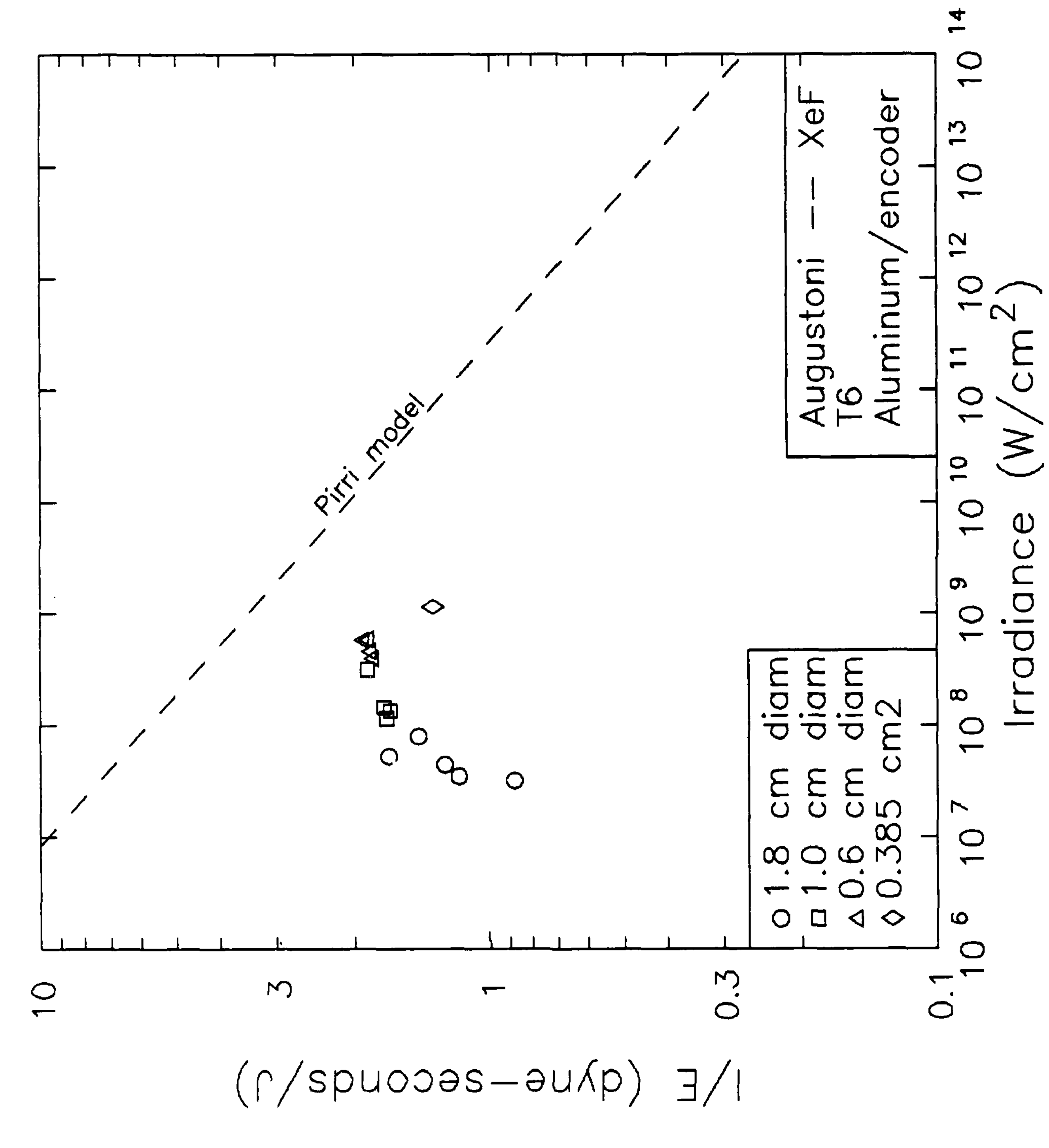
Measurement technique: (A) beam encoder (a rotating device, the impulse setting a long beam into rotation and the rotation speed indicated by an optical shaft encoder); (B) LVT (linear velocity transducer).

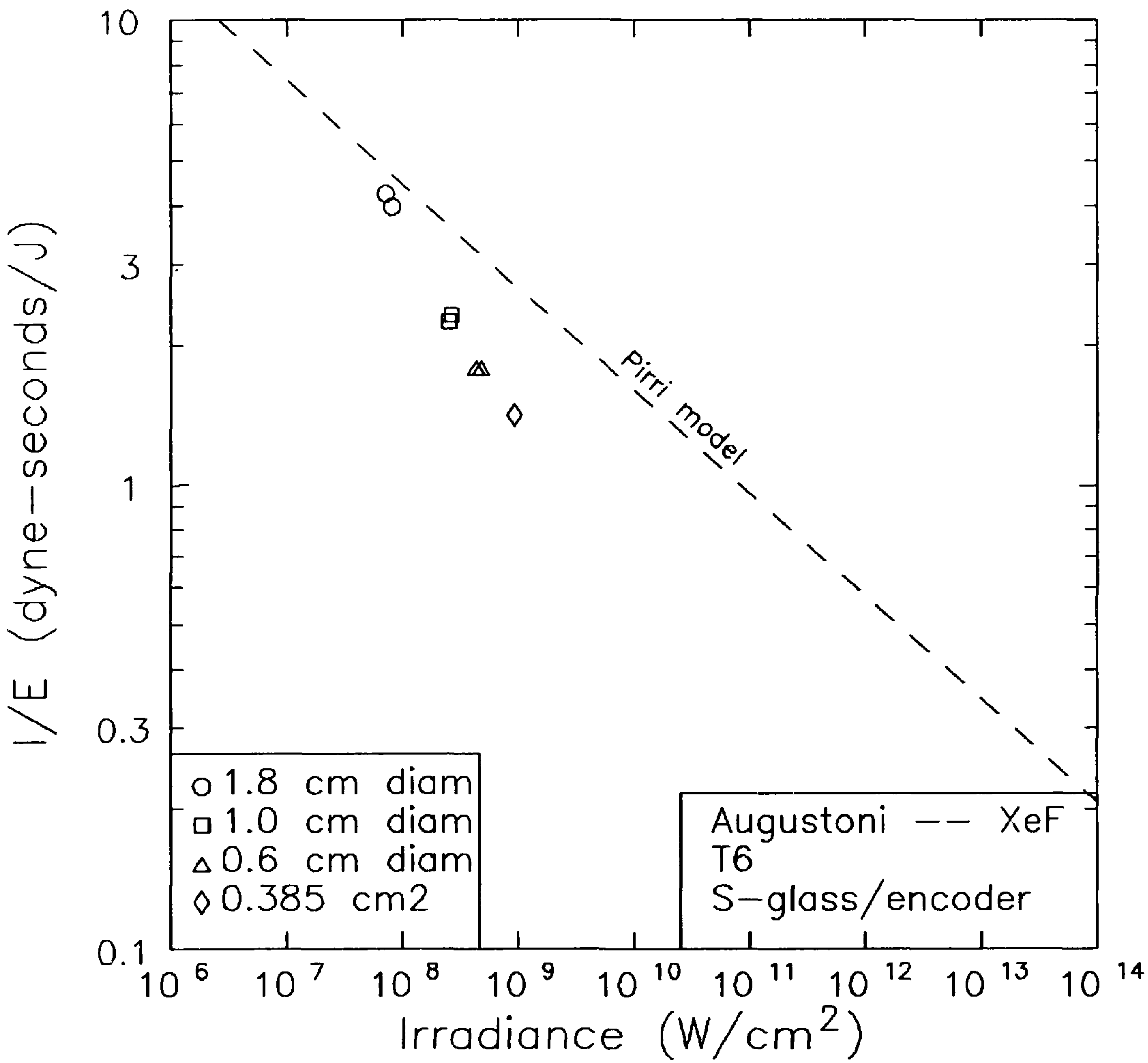
Table caption: "Summary of beam encoder impulse data"; "summary of LVT impulse data".

Comments: These data are characterized by a relatively large spot diameter and long pulse duration, in the ultraviolet. The aluminum data for the larger spots appear to be affected by threshold effects, while the s-glass epoxy data are not, though an alternative explanation for the high coupling on epoxy at low irradiance is ablation prior to plasma ignition. The millimeter-spot data show significantly higher coupling than the trend of the large-spot data, supporting the model prediction of coupling increasing with decreasing spot diameter (as the -1/9 power of the diameter).

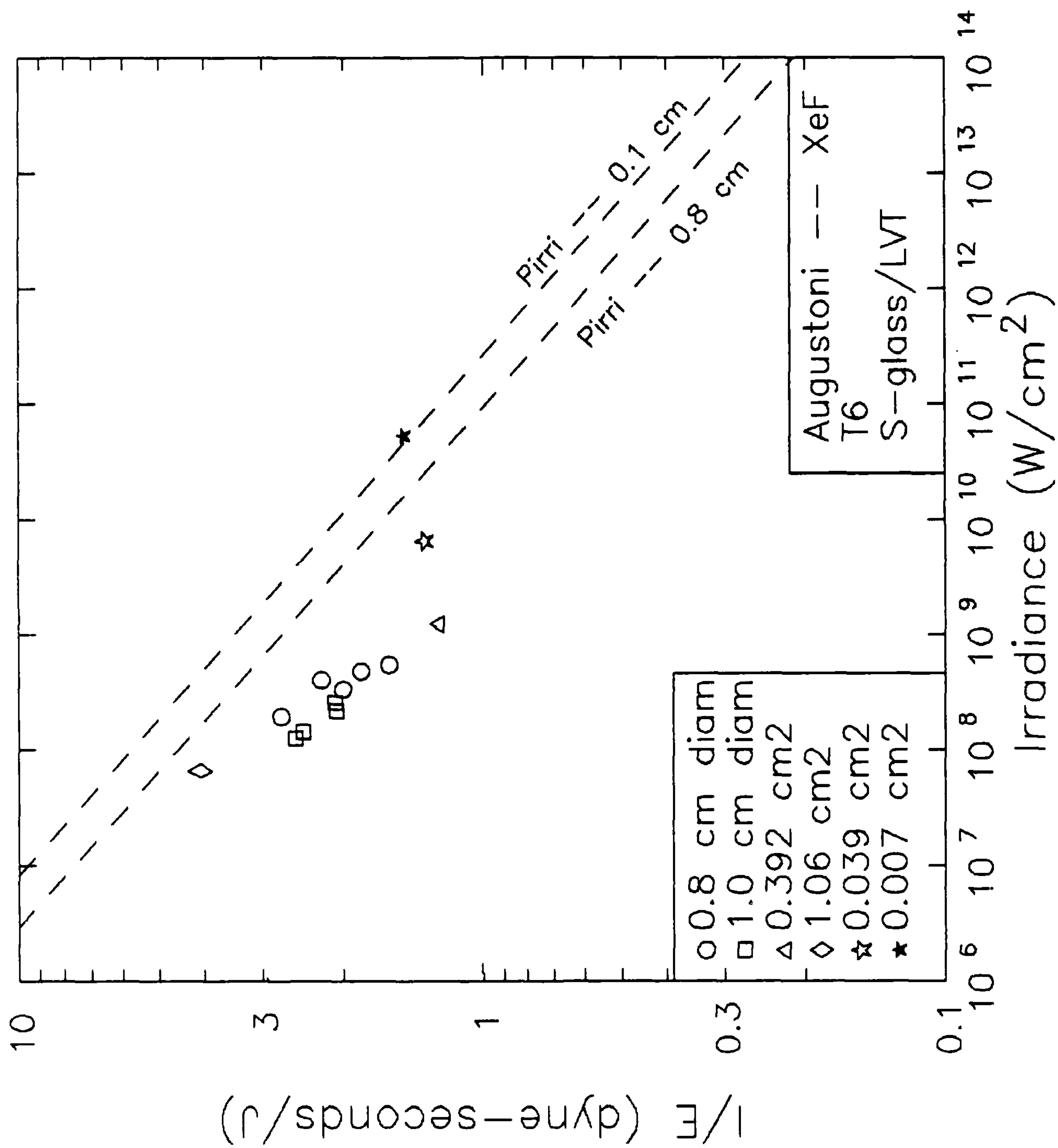


Augustoni --- XeF
T6
Aluminum/LVT
Pirri --- 0.1 cm
Pirri --- 0.8 cm
o 0.8 cm diam
□ 1.0 cm diam
△ 0.392 cm2
◇ 0.037 cm2
☆ 0.007 cm2
Irradiance (W/cm2)
I/E (dyne-seconds/J)


Pirri model
o 1.8 cm diam
□ 1.0 cm diam
△ 0.6 cm diam
◇ 0.385 cm2
Augustoni — XeF
T6
Aluminum/encoder
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}



10
3
1
0.3
0.1
I/E (dyne-seconds/J)
Pirri model
o 1.8 cm diam
□ 1.0 cm diam
△ 0.6 cm diam
◊ 0.385 cm2
Augustoni -- XeF
T6
S-glass/encoder
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
Irradiance (W/cm2)



I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm2)
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
Pirri --- 0.1 cm
Pirri --- 0.8 cm
Augustoni --- XeF
T6
S-glass/LVT
0.8 cm diam
1.0 cm diam
0.392 cm2
1.06 cm2
0.039 cm2
0.007 cm2

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Reference # : VERAC

Authors : Ermer, P.G., Heckler, R.T., Rudder, R.R.

Citation: "An experimental investigation of impulse production by a pulsed XeF laser", AFWL TR (to be published)

Institution: Air Force Weapons Laboratory, Albuquerque NM; and Verac, Albuquerque NM

Experimental Conditions:
- Laser: Maxwell Laboratories 2-meter excimer (KrF)
  - Wavelength: 0.35 μm
  - Pulse energy: 76 J
  - Pulse duration: 1.8 μs
- Intensity range: $1 \times 10^8 - 1 \times 10^9$ W/cm^2
- Atmosphere: vacuum, not specified

Spot dimensions: 0.036 to 0.25 cm^2 area

Target materials: Aluminum, 2026, 6061, and 1100 alloys; S-glass epoxy

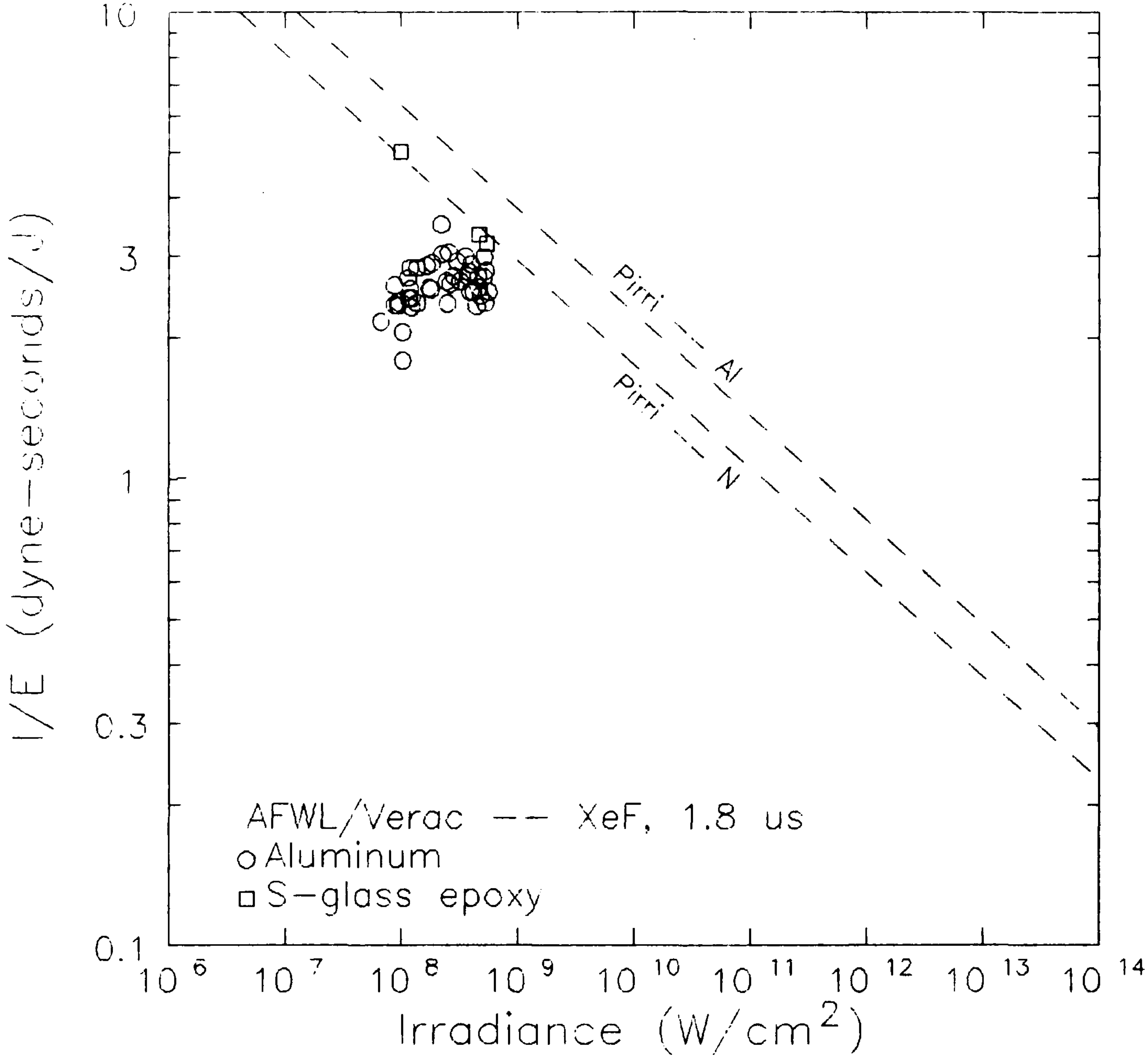
Target dimensions: 0.4 to 2.0 cm diam

Measured quantities: impulse

Measurement technique: linear velocity transducer

Table caption:

Comments: These data were taken under conditions identical to those of Wilson, including the use of the same laser facility, in order to confirm or refute his rather high I/E values (see T2). The impulse gauge was the AFWL LVT instead of the Maxwell sensor. The I/E values obtained with the LVT are in better agreement with other XeF results (e.g., Augustoni et al., T6) than with Wilson's measurements, suggesting that the Wilson data are, for reasons which remain unknown, anomalously high.



I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
Irradiance (W/cm2)
Pirri -- Al
Pirri -- N
AFWL/Verac -- XeF, 1.8 us
Aluminum
S-glass epoxy

Reference # : Sprite I

Authors : R.S. Dingus

Citation: "Sprite II Experiments", presentation at the "Photon Torpedo" Effects Meeting, 9-13 December 1985, Marina del Rey CA

Institution: Los Alamos National Laboratory, Los Alamos NM

Experimental Conditions:

Laser: e-beam KrF (Rutherford-Appleton Laboratory, UK)
Wavelength: 0.25 μm
Pulse energy: 10-120 J
Pulse duration: 50 ns

Intensity range: 6×10^7 - 2×10^{12} W/cm^2
Atmosphere: vacuum, 0.05 - 5 Torr (70 μbar - 7 mbar)

Spot dimensions: 0.1 to 2.5 cm diameter, variable

Target materials: Aluminum, titanium, TBR (titanium-bearing resin), graphite epoxy, carbon phenolic, Kevlar epoxy, silica phenolic, Vamac, and Lucite

Target dimensions: large compared to laser spot; not specified

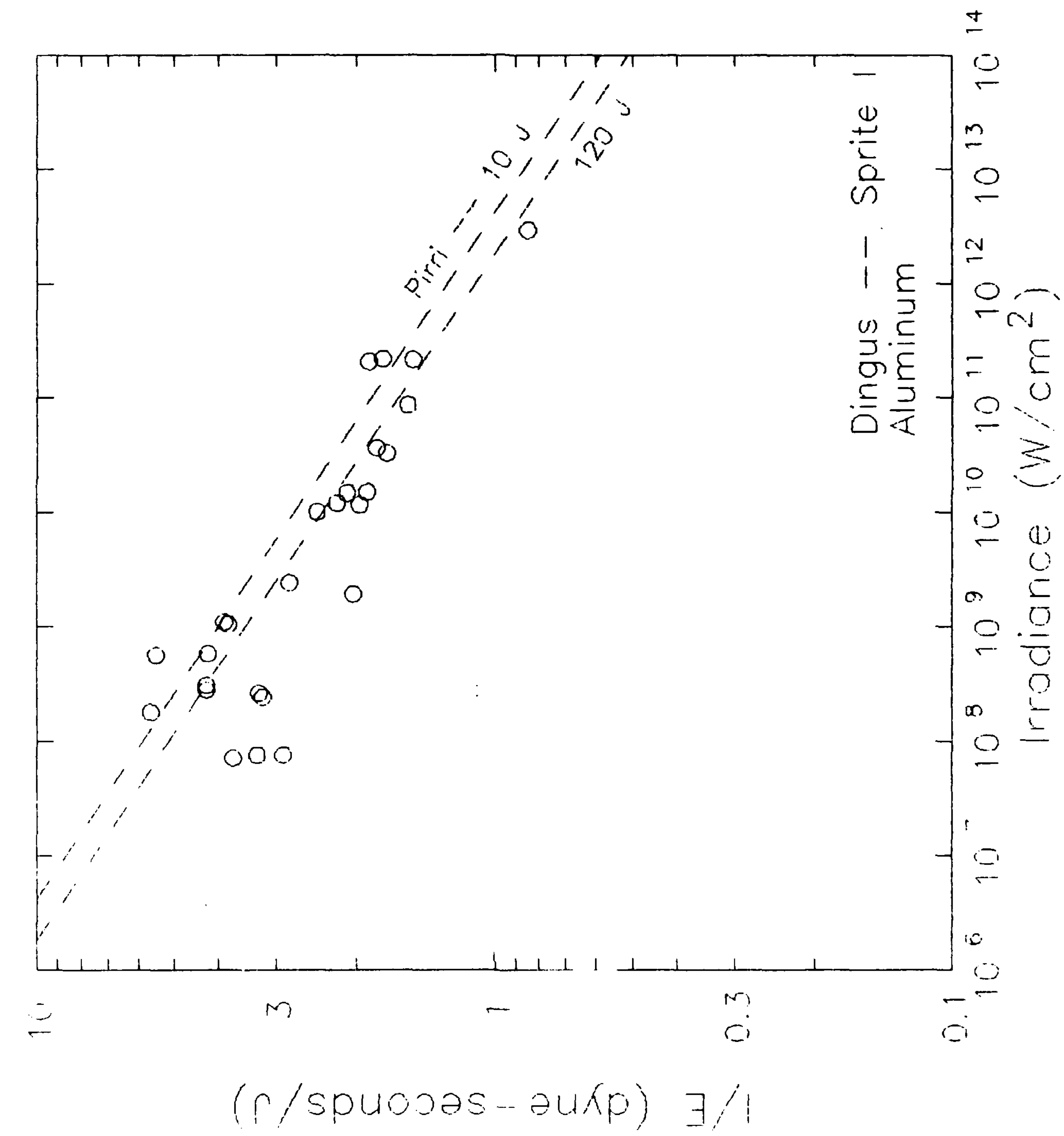
Measured quantities: impulse

Measurement technique: Not given

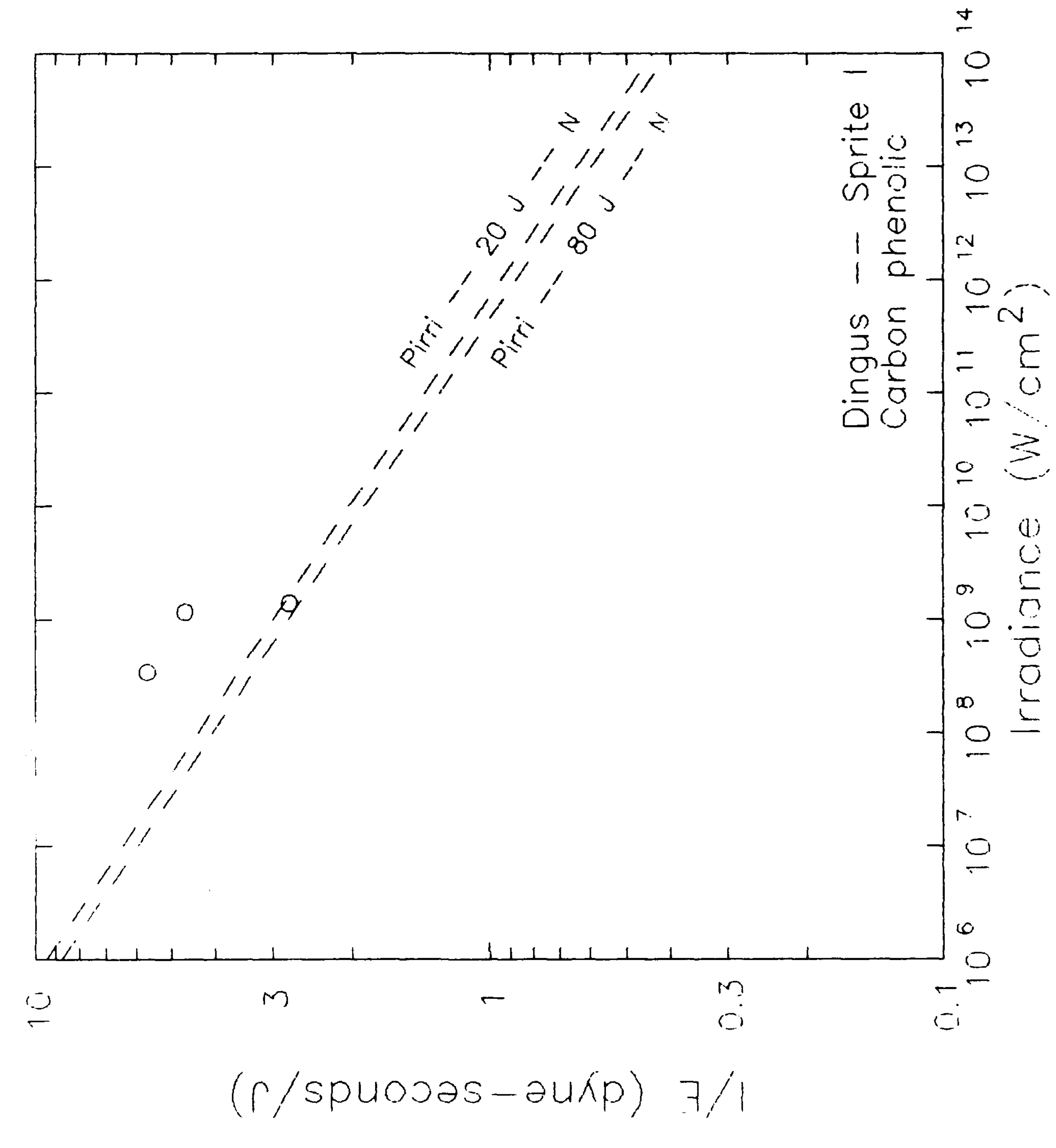
Figure caption: "I/F vs. F, Sprite I, normal incidence, various materials."

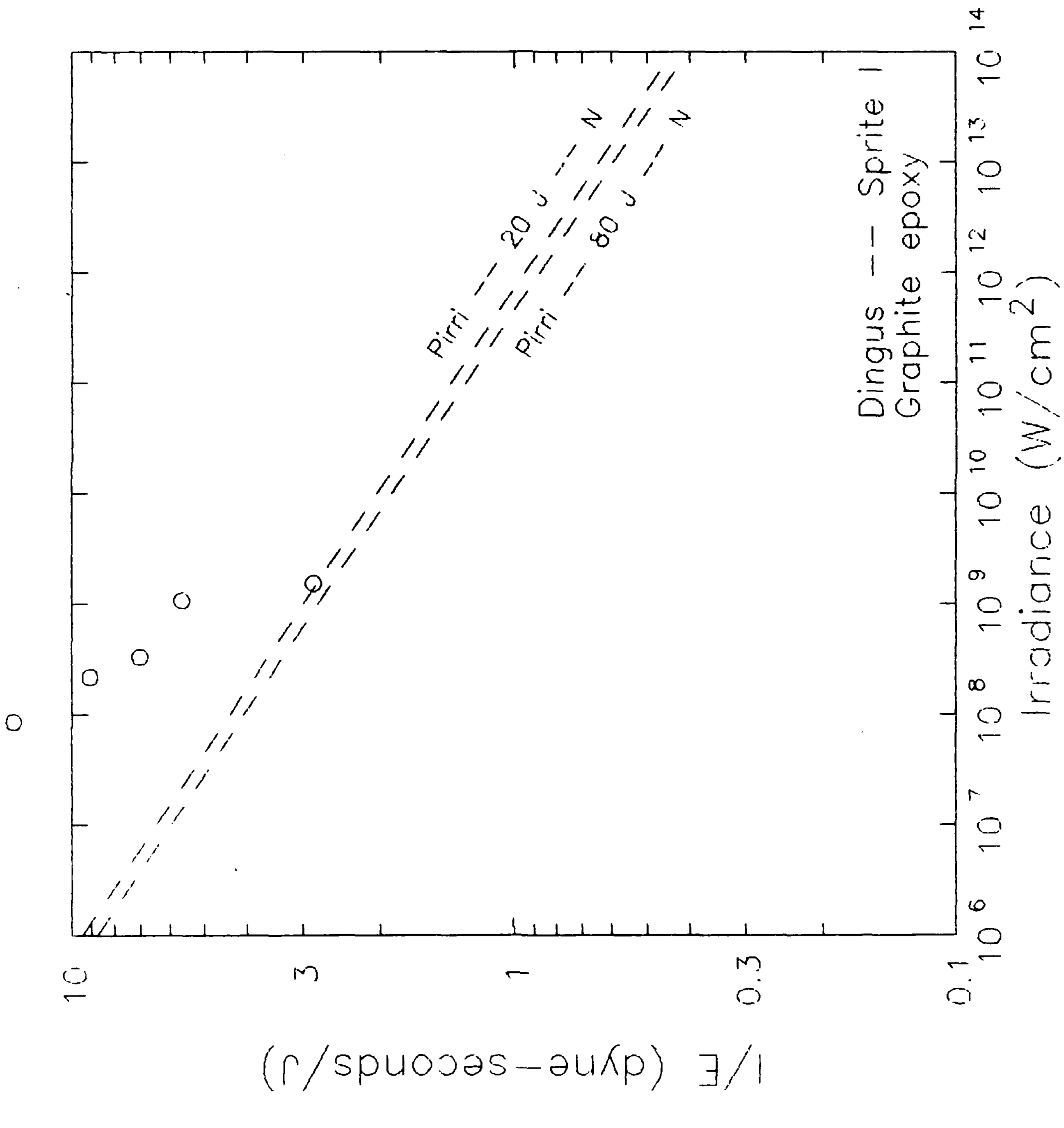
Comments: The figures show the data and the Pirri model line calculated for fixed pulse energy instead of fixed spot diameter, a condition which yields a logarithmic slope of -1/6 instead of -2/9. The actual dependence of coupling on irradiance appears to be somewhat weaker than predicted; the coupling at the lower irradiances is lower than the model predicts, while the coupling at high irradiance is fairly close. Considering the simplicity of the model, the fit is remarkably good.

With the obvious exceptions, these materials consist largely of C, N, and O, which have atomic weights so similar that the effect on the Pirri model calculations is negligible. Carbon (A=12) was used for the carbonaceous materials, nitrogen (A=14) for the polymers. The model predicts significantly higher coupling for heavier atoms, in proportion to the atomic mass to the power 7/18. For titanium, for example, with A=47.9, the coupling ought to be a factor 1.7 greater than for carbon. No such correlation can be drawn from the data.

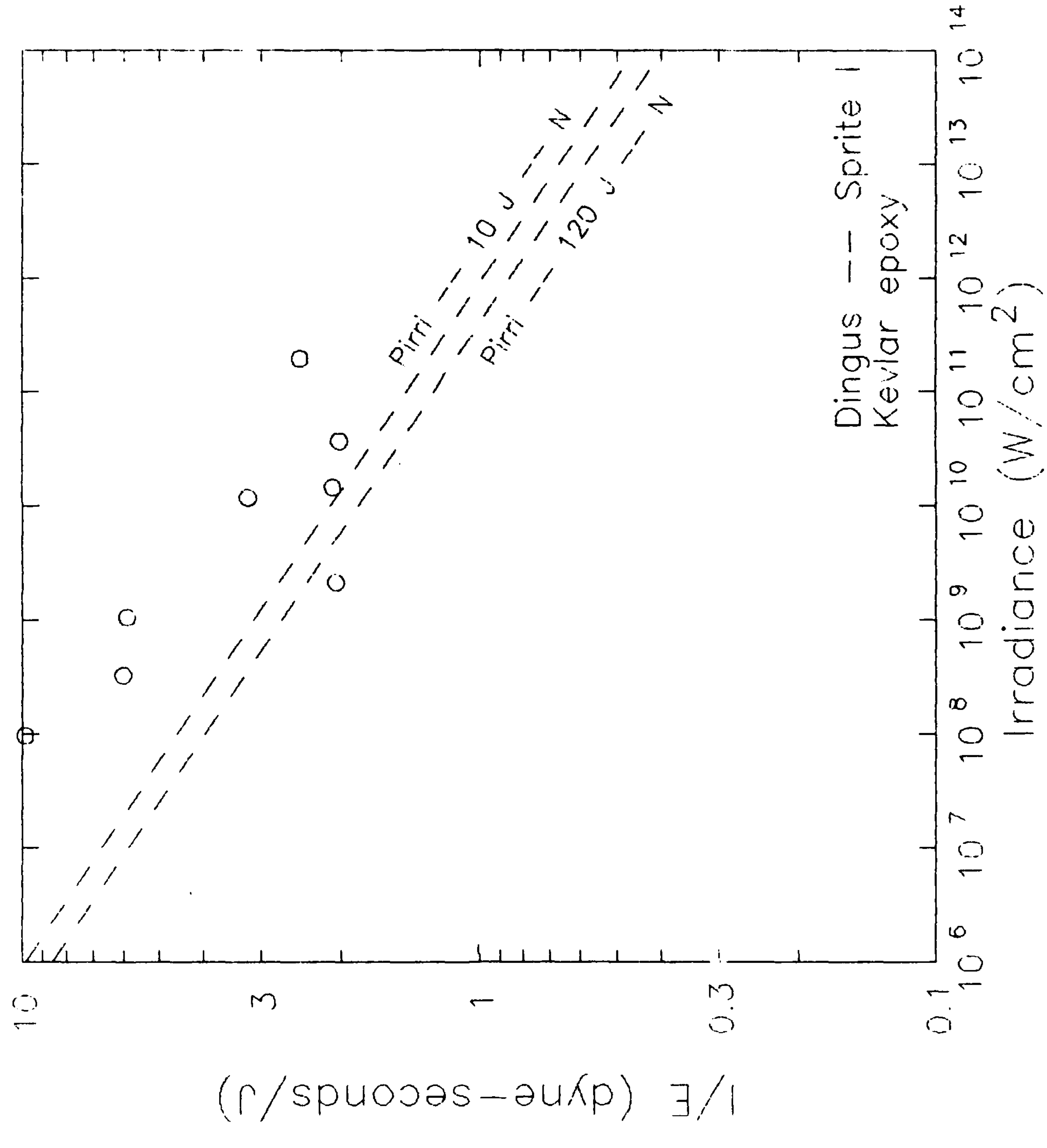


Dingus — Sprite I
Aluminum
Pirri --- 10 J
120 J
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10
3
1
0.3
0.1

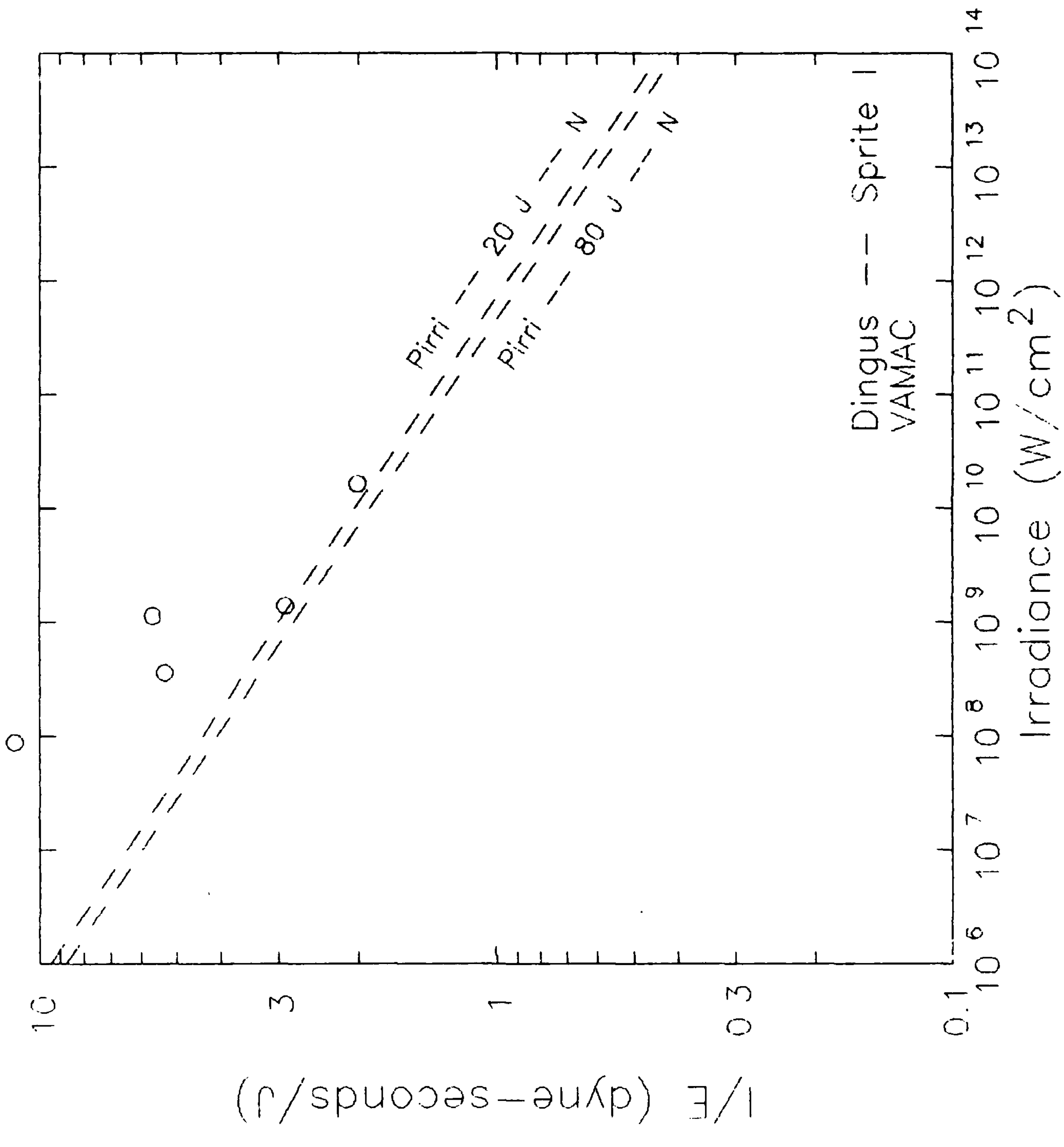

I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm²)
10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14
Pirri -- 20 J -- N
Pirri -- 80 J -- N
Dingus -- Sprite I
Carbon phenolic

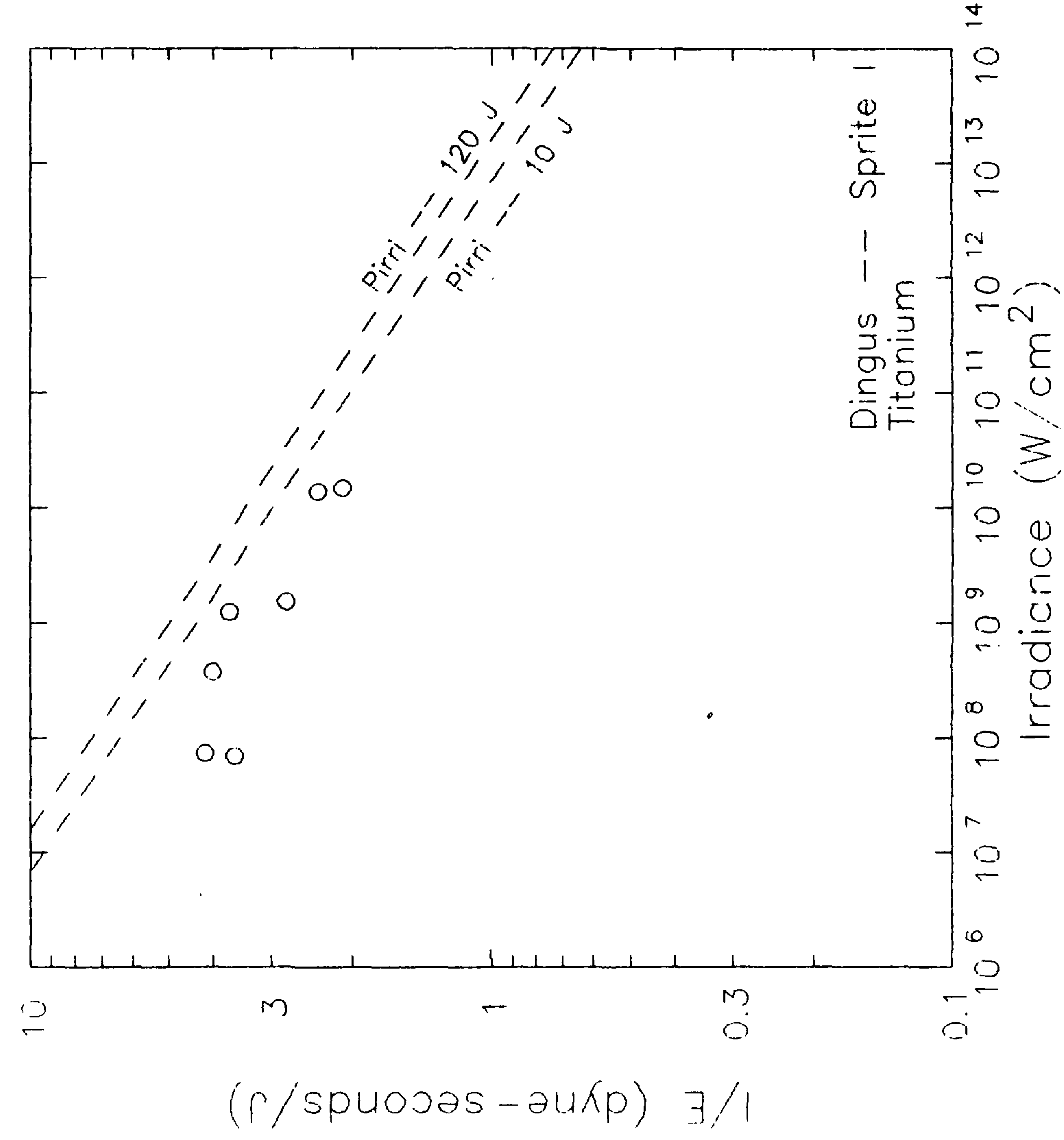


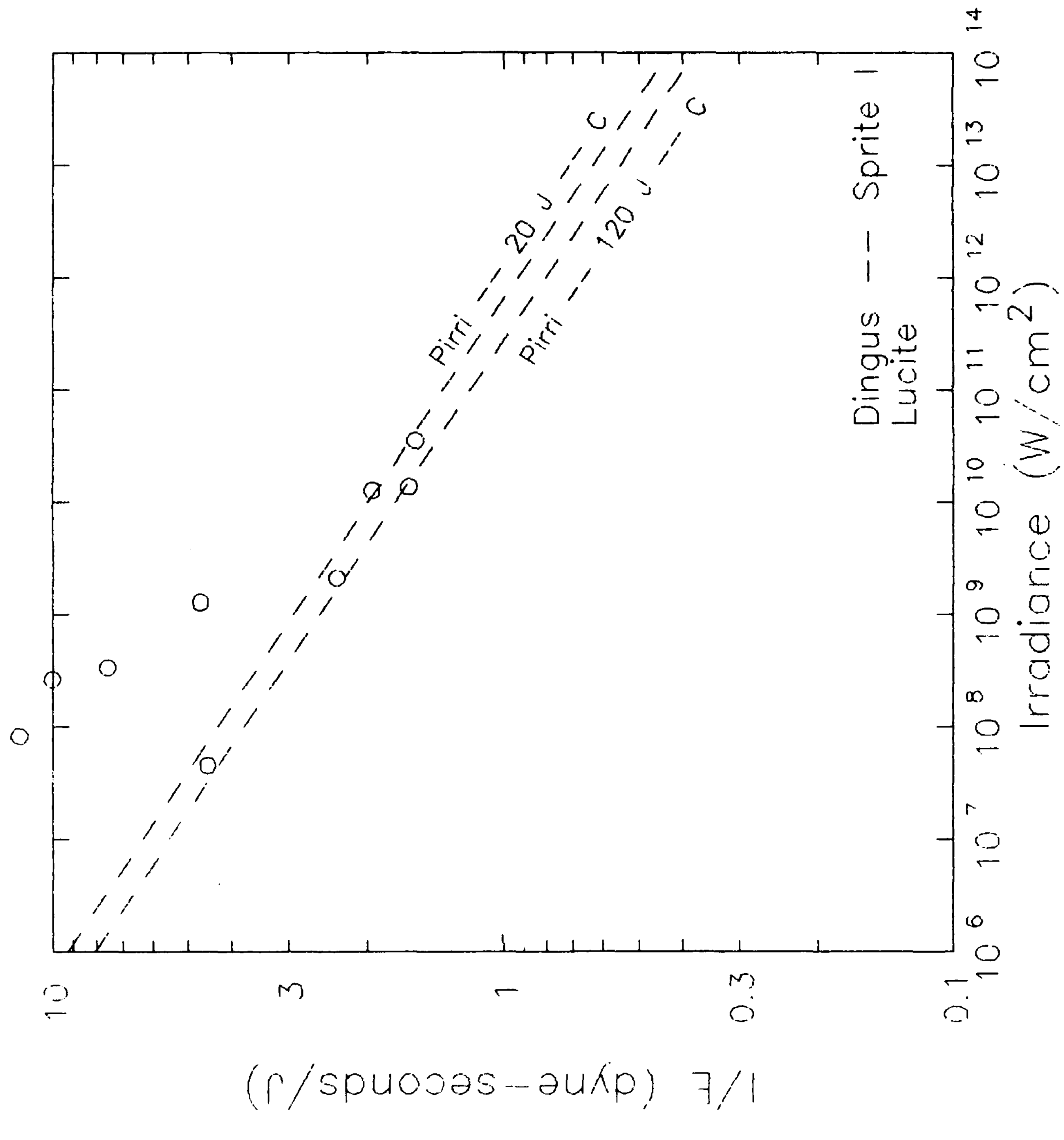
Dingus -- Sprite I
Graphite epoxy
Pirri -- 20 J -- N
Pirri -- 80 J -- N
10
3
1
0.3
0.1
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
Irradiance (W/cm2)
I/E (dyne-seconds/J)



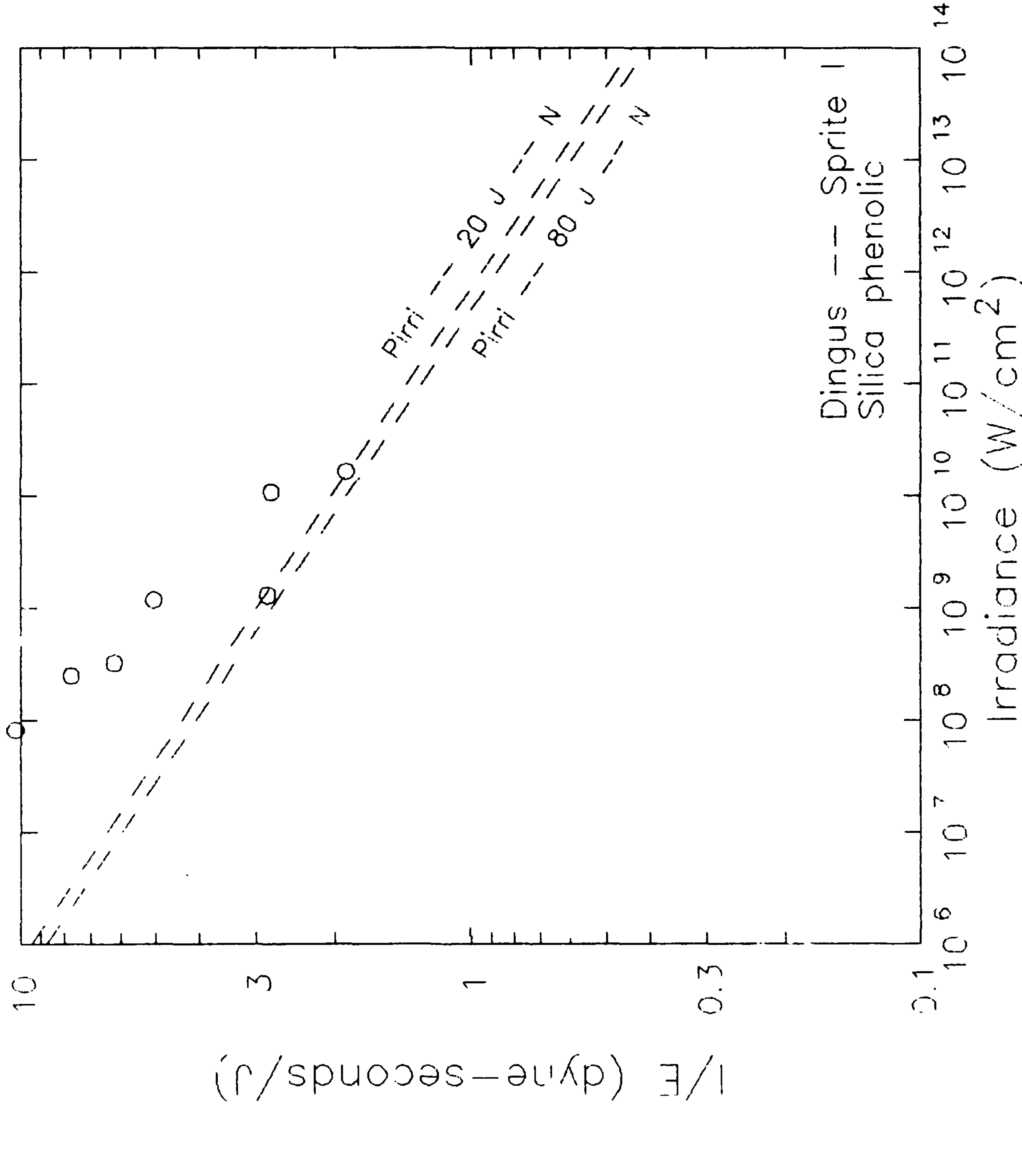
Dingus — Sprite I
Kevlar epoxy
Pirri 10 J
Pirri 120 J
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Irradiance (W/cm^2)
I/E (dyne-seconds/J)


Pirri -- 20 J -- N
Pirri -- 80 J -- N
Dingus -- Sprite I
VAMAC
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

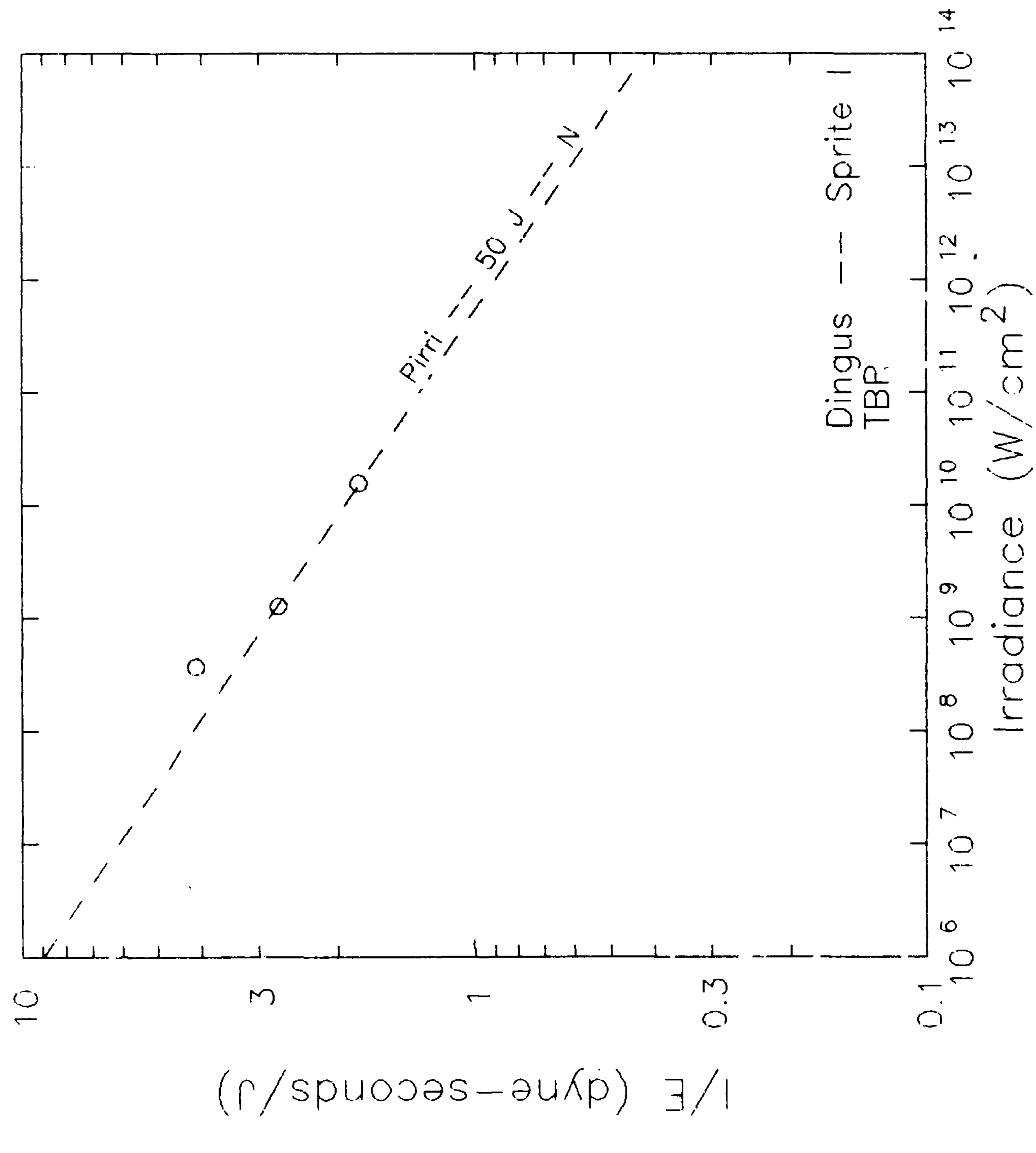

Dingus -- Sprite I
Titanium
Pirri 120 J
Pirri 10 J
Irradicnce (W/cm²)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴



I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm^2)
10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14
Pirri 20 J
Pirri 120 J
Dingus — Sprite I
Lucite



Dingus --- Sprite I
Silica phenolic
Pirri -- 20 J -- N
Pirri -- 80 J -- N
Irradiance (W/cm²)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴



Pirri
50 J
N
Dingus — Sprite I
TBP
10
3
1
0.3
0.1
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
Irradiance (W/cm 2)
I/E (dyne-seconds/J)

Reference # : Sprite II

Authors : R.S. Dingus

Citation: "Sprite II Experiments", presentation at the "Photon Torpedo" Effects Meeting, 9-13 December 1985, Marina del Rey CA

Institution: Los Alamos National Laboratory, Los Alamos NM

Experimental Conditions:
Laser: e-beam KrF (Rutherford-Appleton Laboratory, UK)
Wavelength: 0.25 μm
Pulse energy: 100 J
Pulse duration: 50 ns
Intensity range: 2×10^8 - 6×10^{12} W/cm^2
Atmosphere: vacuum, level not specified; also air, 1 Torr (1.3 mbar), 10 Torr (13 mbar), and 760 Torr (1.01 bar).

Spot dimensions: 0.1 to 2.5 cm diameter, variable

Target materials: Aluminum

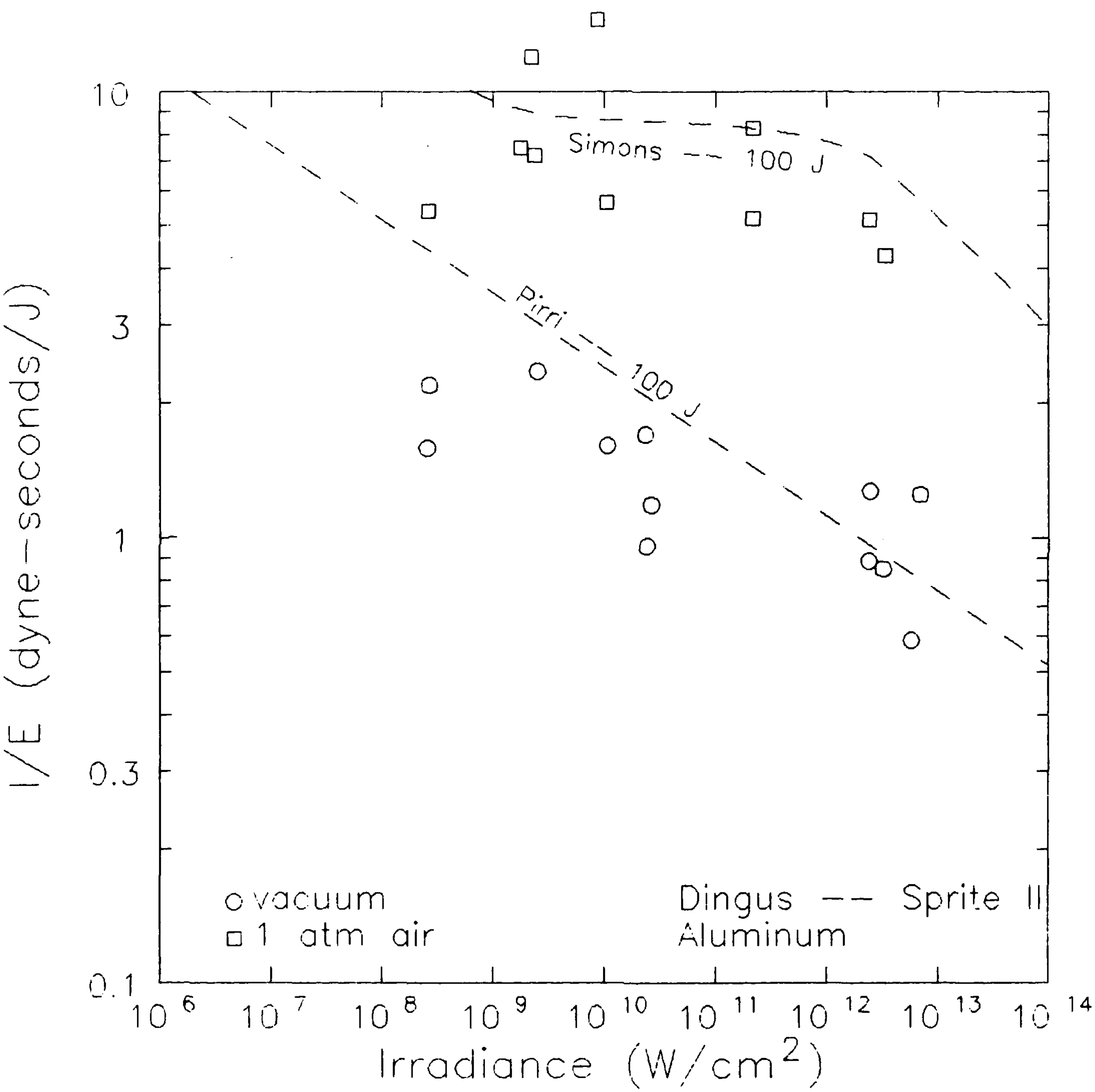
Target dimensions: large compared to laser spot

Measured quantities: impulse

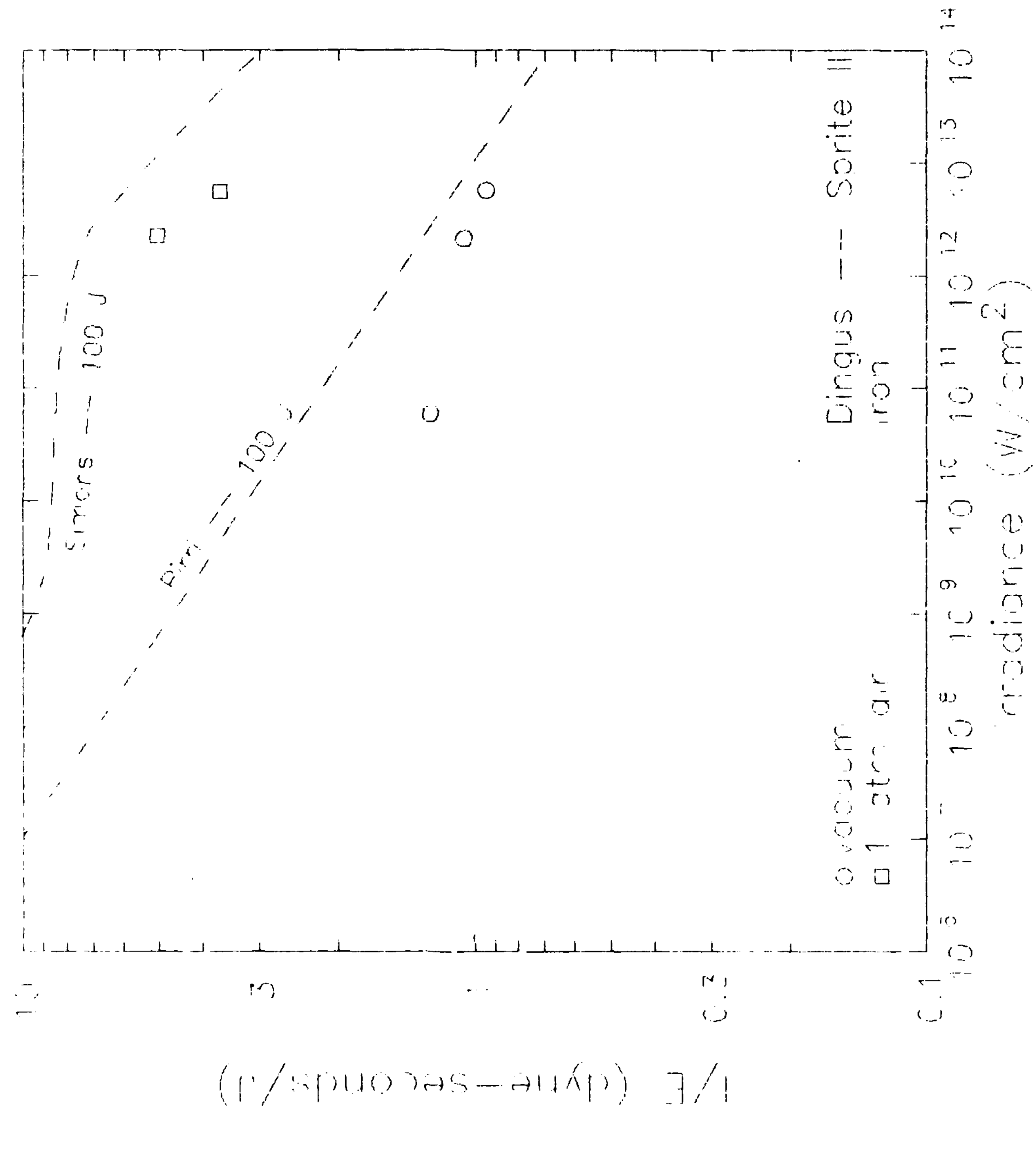
Measurement technique: Not given

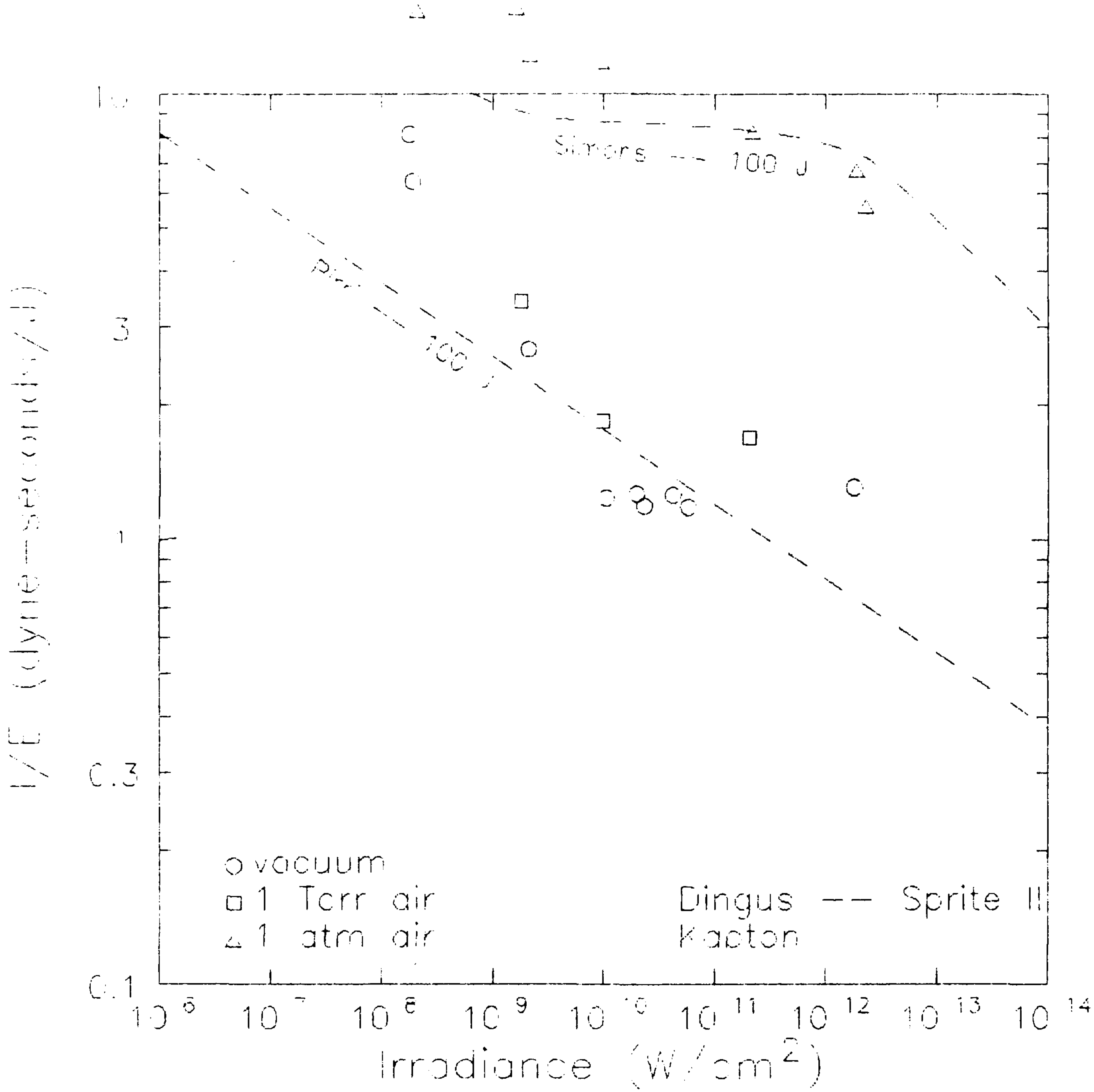
Figure caption: "I/F vs. F, Sprite II (100 J), normal incidence, vacuum and atmospheric pressure, various materials."

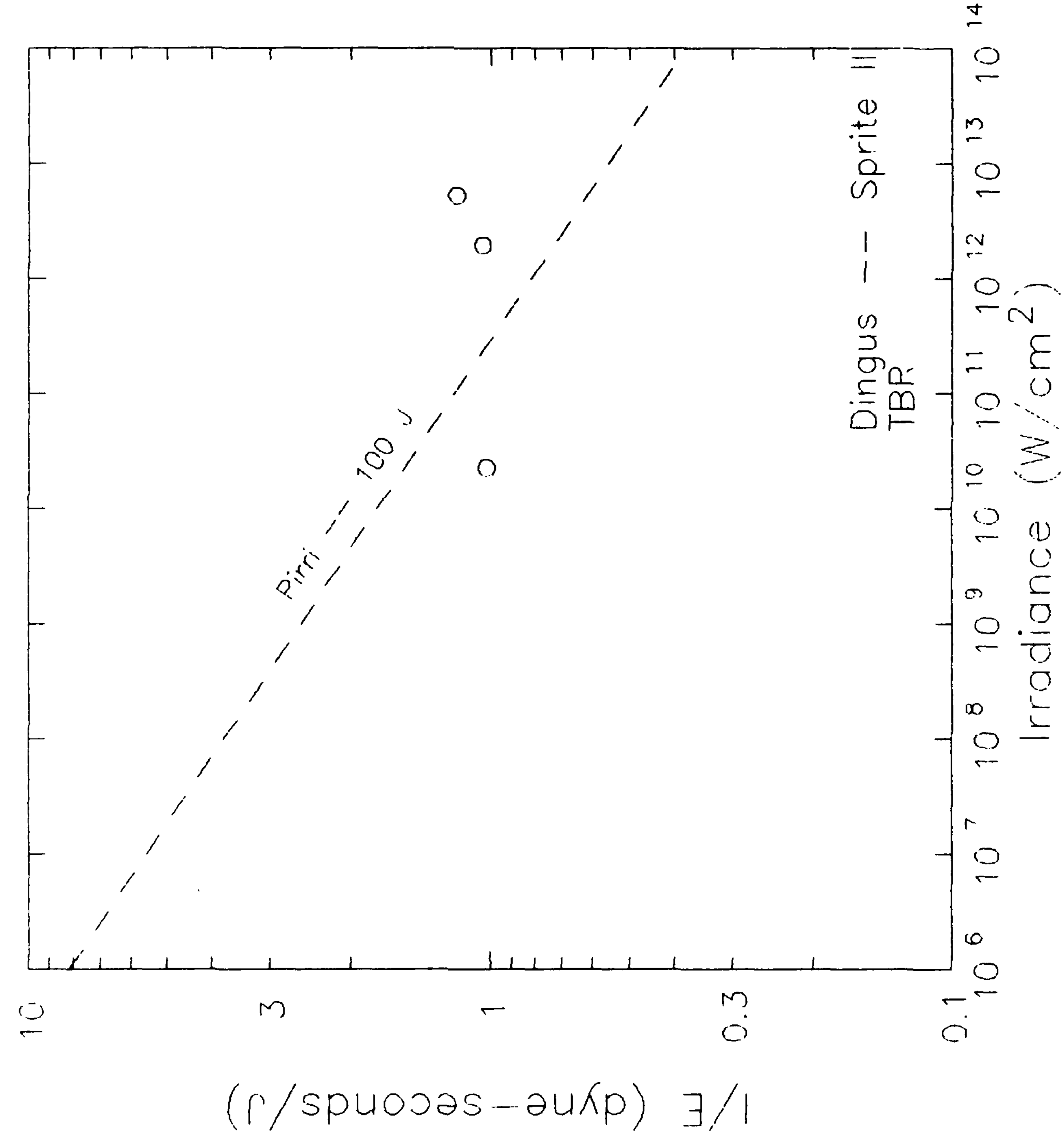
Comments: This experimental series was a successor to Sprite I, with somewhat greater pulse energy. Similar conclusions obtain. The atomic weight dependence ought to be clear with tantalum (A=181), which should show coupling almost three times that of carbon; no such dependence is evident. The results in air show the effect of a small spot on a large target, yielding apparently high impulse coupling, due to radial expansion of the air blast wave across the target surface. The local impulse delivery within the laser spot will be little different in air and in vacuum, and the high coupling indicated here in air will be of no use for a large laser attempting to deliver penetration-level impulses.

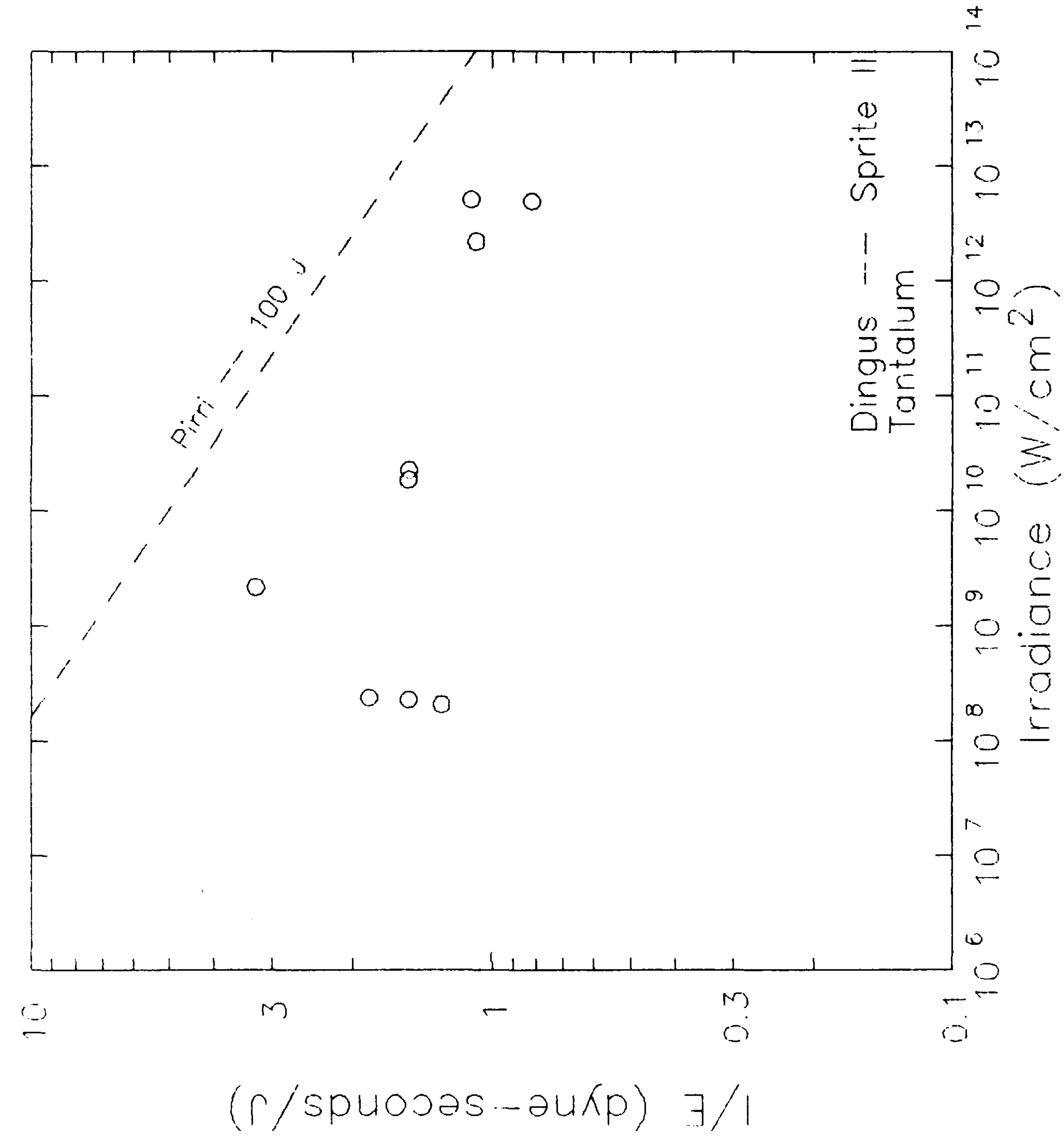


I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Simons -- 100 J
Pirri -- 100 J
o vacuum
□ 1 atm air
Dingus -- Sprite II
Aluminum
10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14}
Irradiance (W/cm^2)

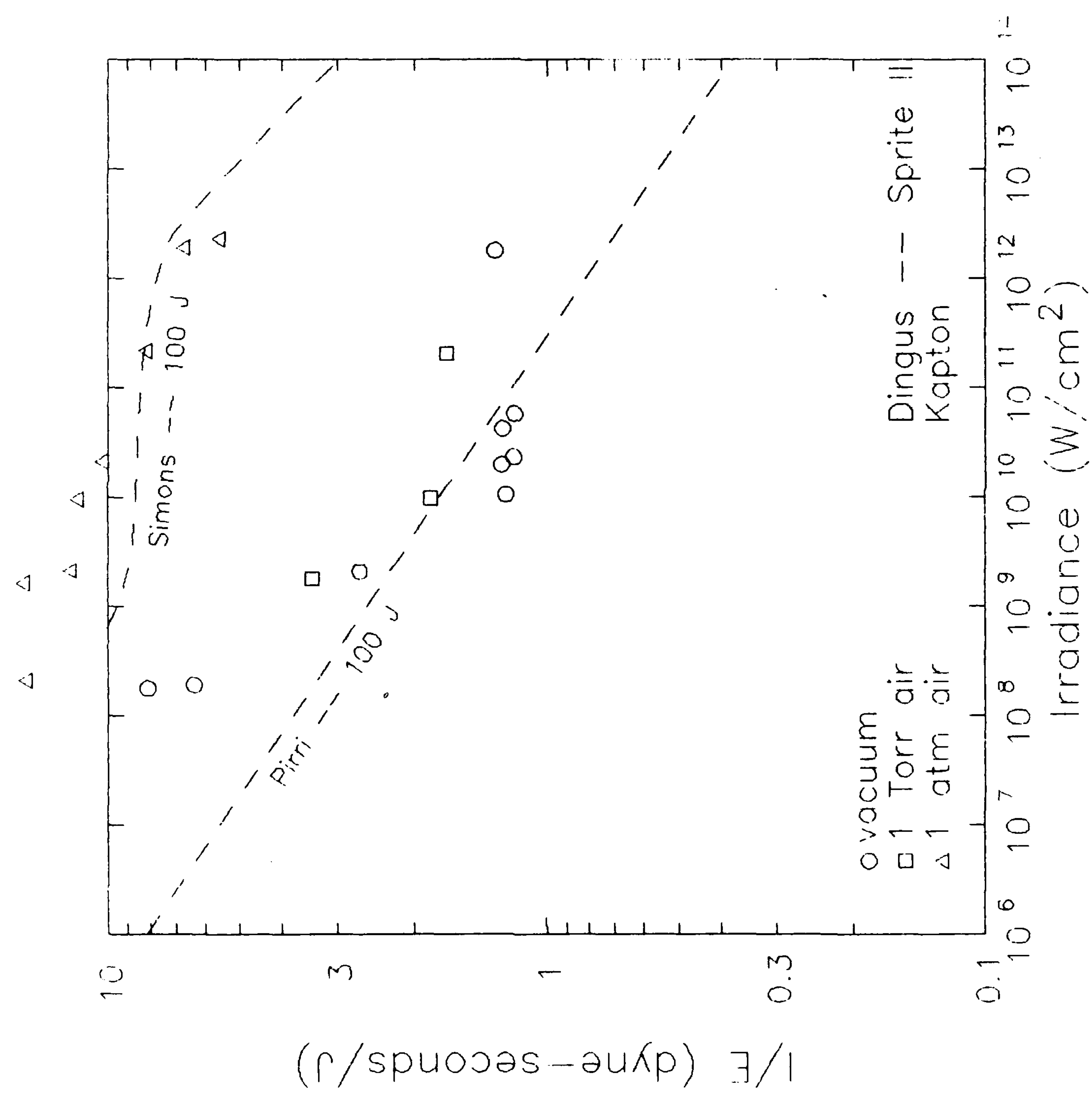

Dingus — Sprite II
iron
o vacuum
□ 1 atm air
100 J
100 J
Irradiance (W/cm^2)
I/E (dyne-seconds/J)


Simons — 100 J
100 J
I/E (dyne-seconds/J)
Irradiance (W/cm2)
vacuum
1 Torr air
1 atm air
Dingus — Sprite III
Kapton
10
3
1
0.3
0.1
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14

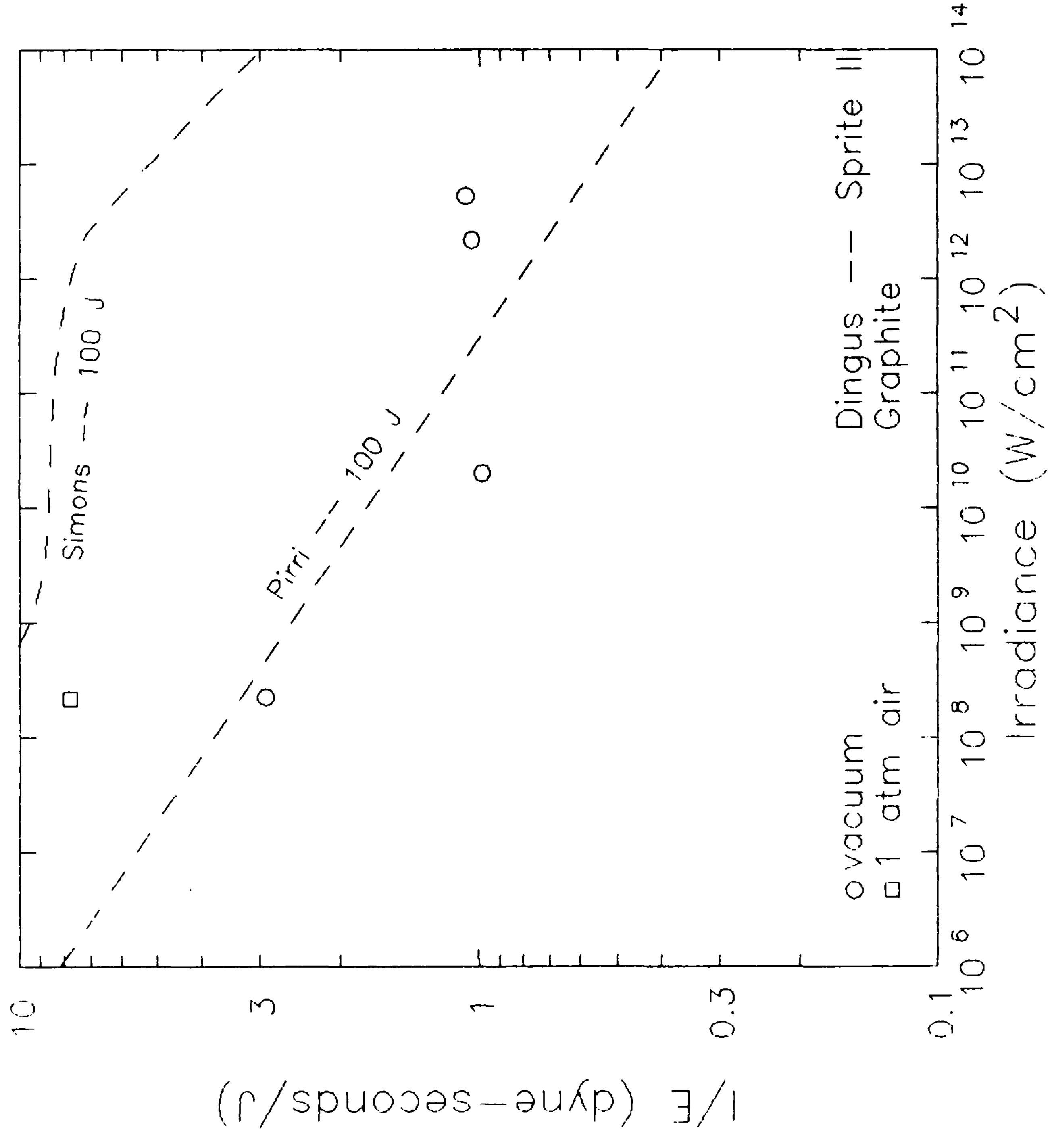

Pirri --- 100 J
Dingus -- Sprite II
TBR
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Irradiance (W/cm^2)

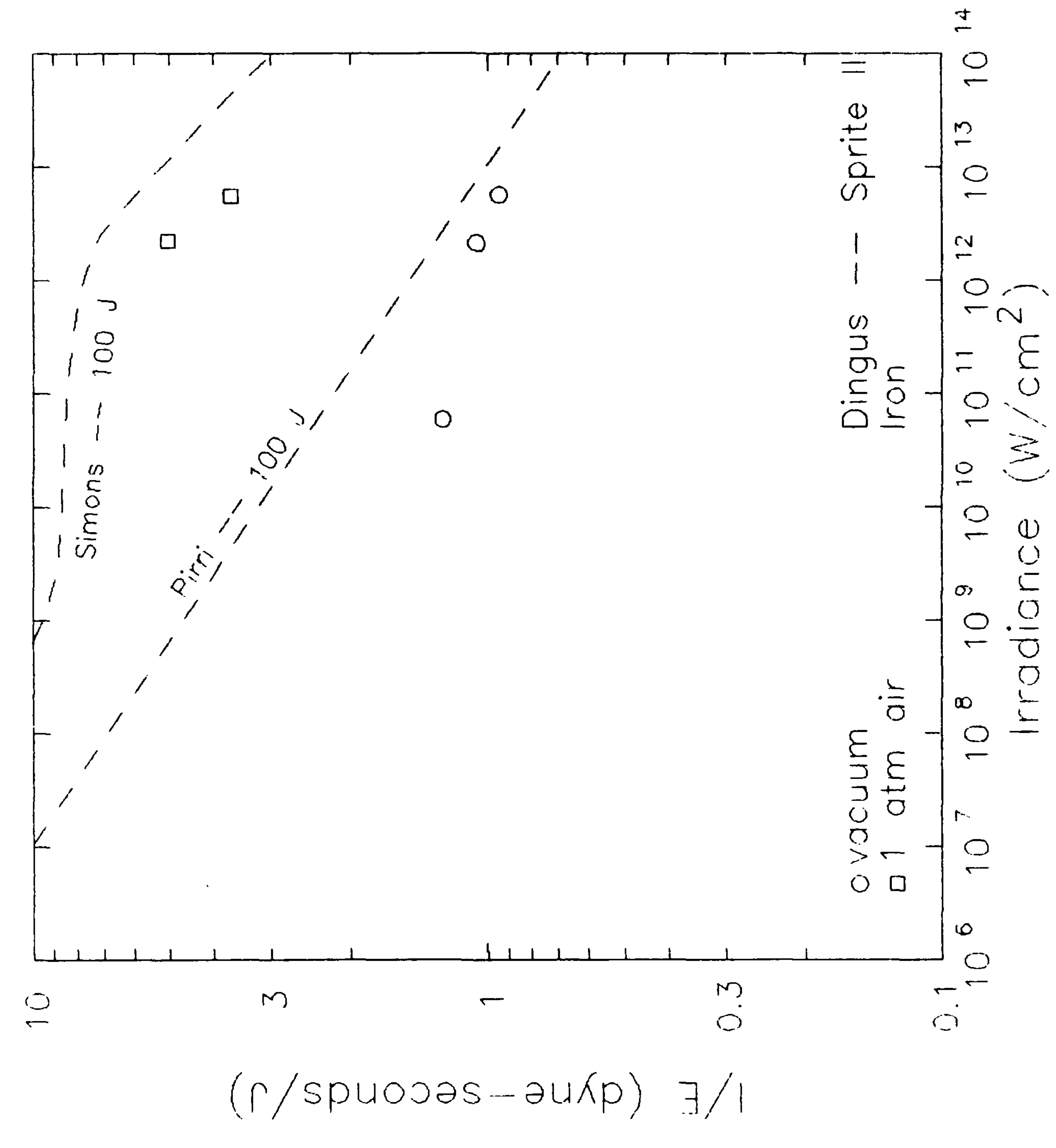


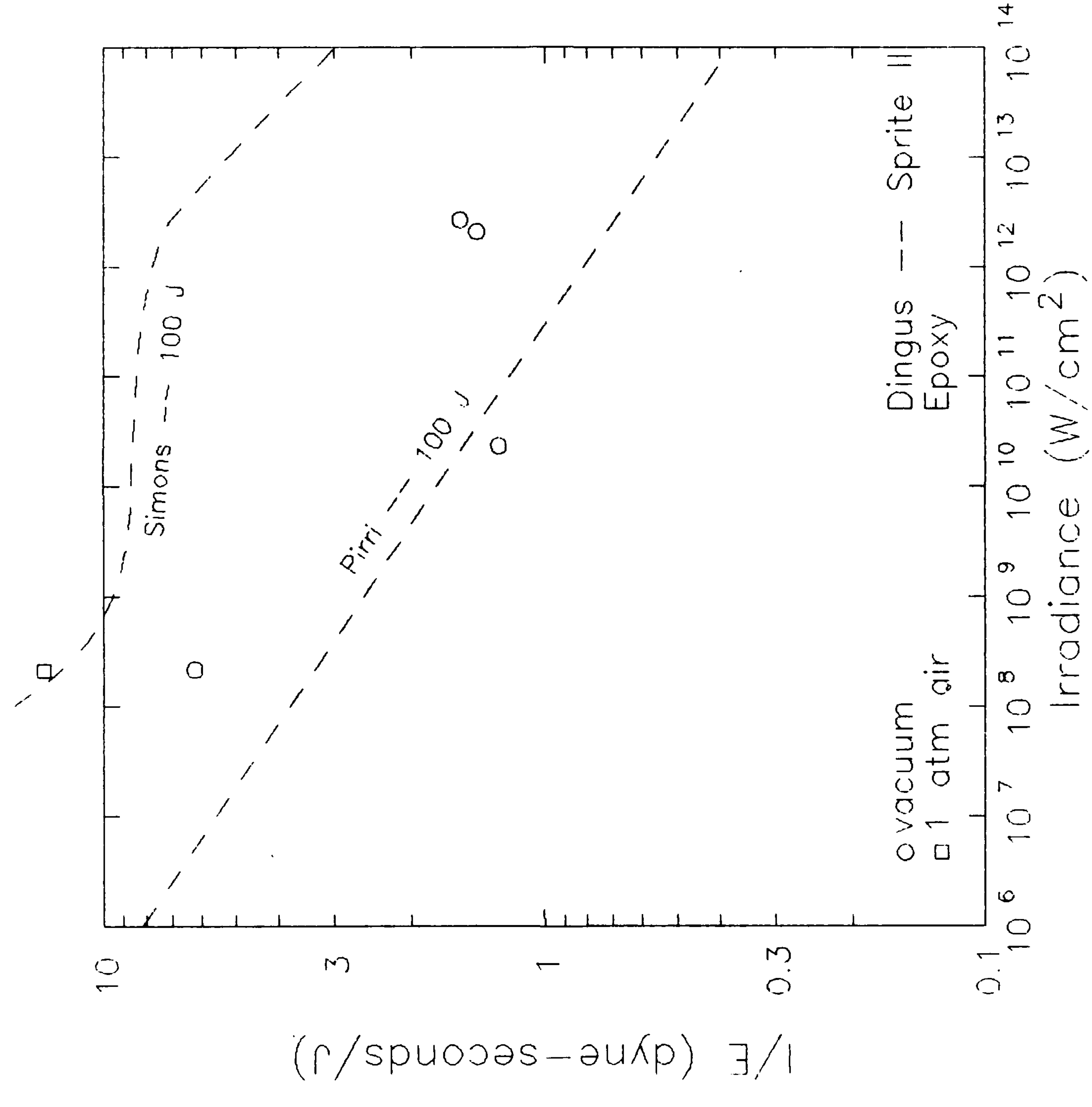
Pirri --- 100 J
Dingus --- Sprite II
Tantalum
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Irradiance (W/cm^2)

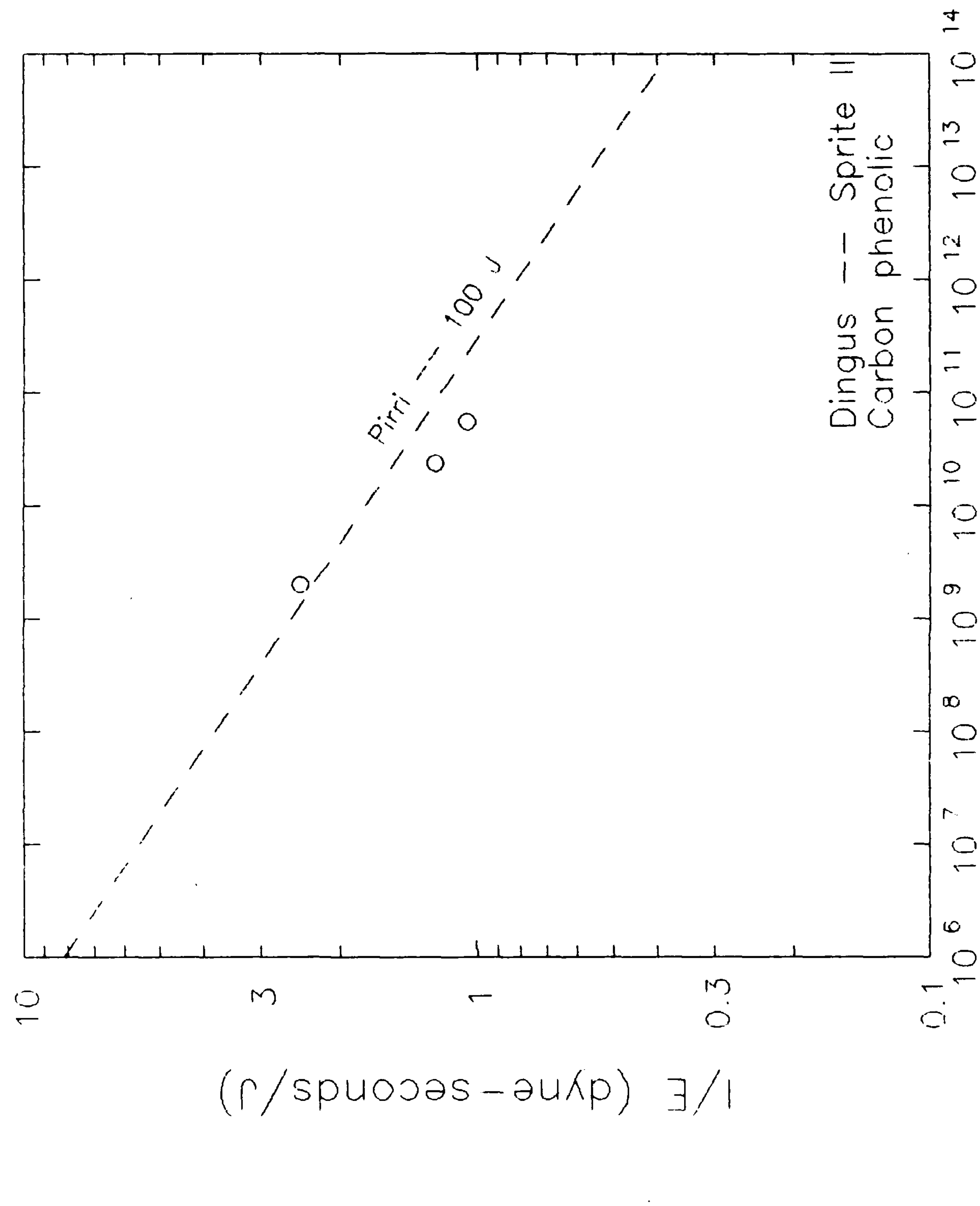


I/E (dyne-seconds/J)
Irradiance (W/cm^2)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
o vacuum
□ 1 Torr air
Δ 1 atm air
Dingus — Sprite II
Kapton
Pirri — 100 J
Simons — 100 J

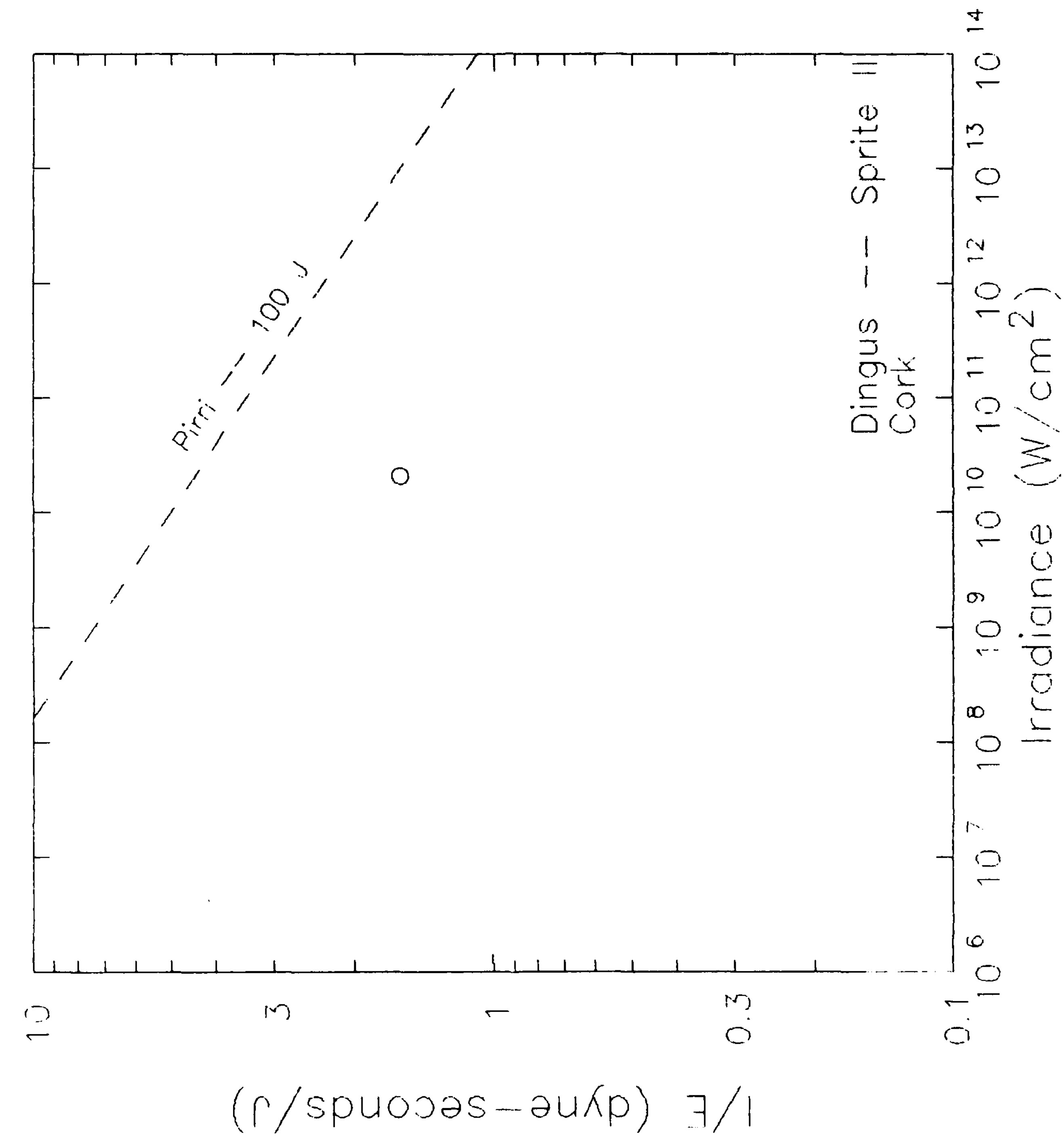

I/E (dyne-seconds/J)
10
3
1
0.3
0.1
Irradiance (W/cm²)
10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴
Simons -- 100 J
Pirri --- 100 J
o vacuum
□ 1 atm air
Dingus -- Sprite II
Graphite


I/E (dyne-seconds/J)
Irradiance (W/cm²)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14
Simons --- 100 J
Pirri --- 100 J
o vacuum
□ 1 atm air
Dingus --- Sprite II
Iron


I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Irradiance (W/cm^2)
Simons --- 100 J
Pirri --- 100 J
○ vacuum
□ 1 atm air
Dingus --- Sprite II
Epoxy



Pirri --- 100 J
Dingus — Sprite II
Carbon phenolic
Irradiance (W/cm^2)
I/E (dyne-seconds/J)


Pirri — 100 J
Dingus — Sprite II
Cork
Irradiance (W/cm^2)
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

Reference # : WILSON

Authors : R.S. Wilson

Citation: "Final Report: Two-meter laser material response measurements", Maxwell Laboratories report MLR-2523 (April 1987)

Institution: Maxwell Laboratories, San Diego CA

Experimental Conditions:

Laser: Maxwell Laboratories 2-meter excimer (KrF)

Wavelength: 0.25 μm

Pulse energy: 150 J

Pulse duration: 1.7 μs

Intensity range: 5×10^8 W/cm^2

Atmosphere: vacuum, not specified

Spot dimensions: 0.225x0.45 cm

Target materials: Aluminum (1100-H118 alloy)

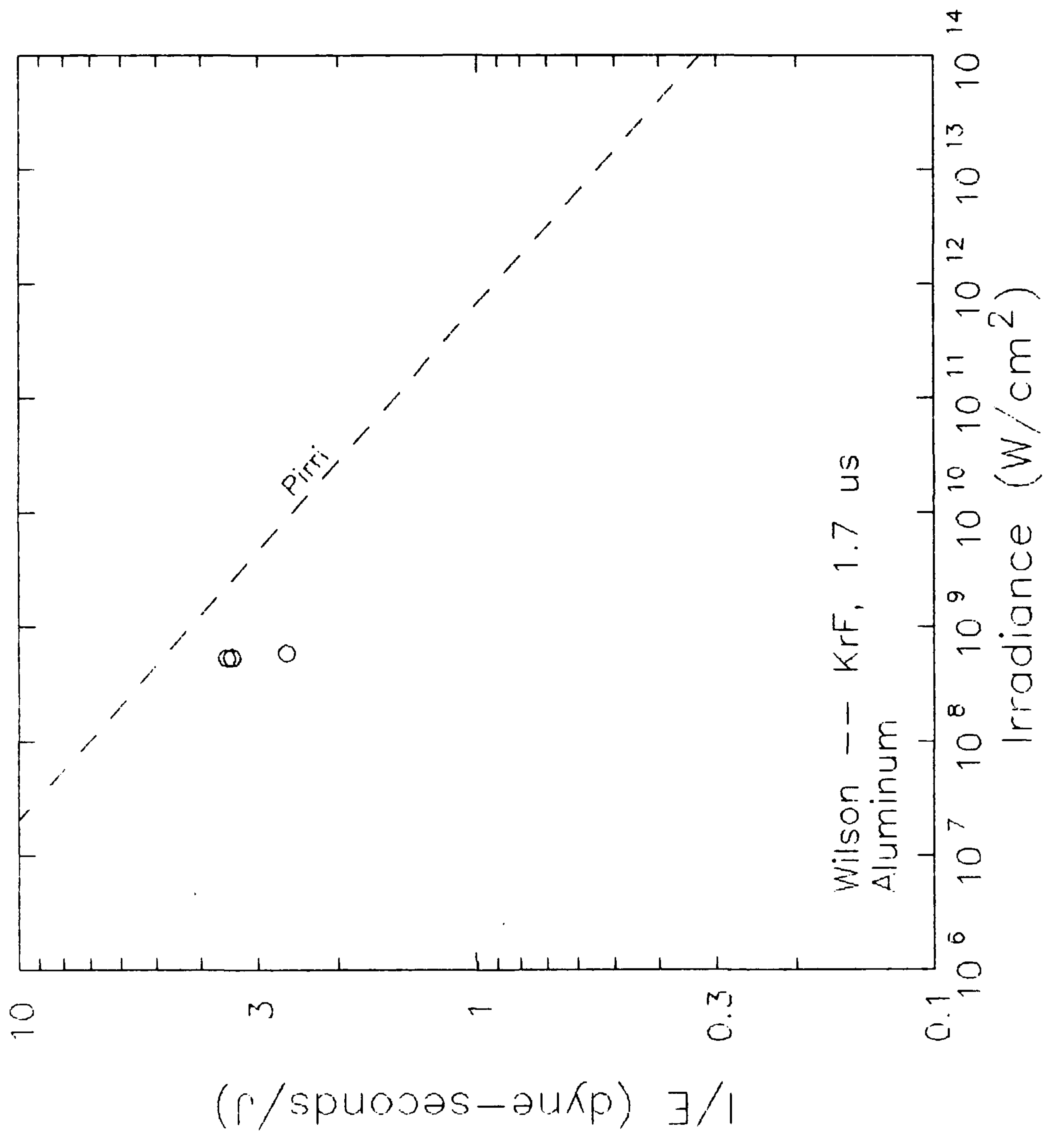
Target dimensions: 0.6 cm diam

Measured quantities: impulse

Measurement technique: ballistic pendulum

Table caption: "Impulse-fluence coupling for aluminum in vacuum, KrF"

Comments: These KrF data are very close to values obtained by Dingus at the same wavelength but with a much shorter (50 ns) pulse, suggesting that there is no significant pulse duration effect in impulse coupling.


Wilson -- KrF, 1.7 us
Aluminum
Pirri
I/E (dyne-seconds/J)
10
3
1
0.3
0.1
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Irradiance (W/cm^2)